Social, Environmental and Economic Impacts of Alternative Energy and Fuel Supply Chains

Christiana Papapostolou

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Heriot-Watt University
School of Engineering and Physical Sciences

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ABSTRACT

Energy supply nowadays, being a vital element of a country’s development, has to independently meet diverse, sustainability criteria, be it economic, environmental and social. The main goal of the present research work is to present a methodological framework for the evaluation of alternative energy and fuel Supply Chains (SCs), consisting of a broad topology (representation) suggested, encompassing all the well-known energy and fuel SCs, under a unified scheme, a set of performance measures and indices as well as mathematical model development, formulated as Multi-objective Linear Programming with the extension of incorporating binary decisions as well (Multi-objective Mixed Integer-Linear programming). Basic characteristics of the current modelling approach include the adaptability of the model to be applied at different levels of energy SCs decisions, under different time frames and for multiple stakeholders. Model evaluation is carried for a set of Greek islands, located in the Aegean Archipelagos, examining both the existing energy supply options as well future, more sustainable Energy Supply Chains (ESCs) configurations. Results of the specific research work reveal the social and environmental costs which are underestimated under the traditional energy supply options' evaluation, as well as the benefits that may be produced from renewable energy based applications in terms of social security and employment.

DEDICATION

This research is primarily dedicated to my family; namely my mother, my father and my sister who have always been there for me, to my closest friends for their constant support, and to my companion for encouraging me the most.

Finally, I dedicate this thesis to myself with pride, relief and happiness.

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DECLARATION STATEMENT

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CHAPTER 1 – INTRODUCTION

With the rising risks of energy supply insecurity and as fossil fuels keep depleting both in quantitative and qualitative fashion, the need for clean, environmentally friendly and uninterruptible energy supply has become a major issue, driving the attention of all interested stakeholders (citizens, Non-Governmental Organisations (NGOs), firms, private investors, policy and decision makers, state or community-oriented), towards renewable and alternative energy sources. To that end, a major issue that has recently arisen concerns the investigation of the maximum potential integration of Renewable Energy Sources (RES) in the existing network, which has up to now mainly relied on conventional fuel supply options.

However, determining the optimum RES penetration levels in a country's fuel mix requires a thorough insight and foresight of the factors and impacts affecting it. In this context, design and operation of novel energy and fuel Supply Chains (SCs) comprises a rather interesting research area, where the SC approach, mainly employed in the production and operations management area, could be applied.

Traditionally the concept of SC and its management (Supply Chain Management-SCM) has been widely applied in the product and chemical industry, seeking to efficiently predict and control all stakeholders involved in the different levels of decision making. Suppliers, producers and consumers along the transportation network, as well as time-varying demand and supply characteristics should all be coordinated, controlled and satisfied simultaneously -especially in terms of economic efficiency- even under conditions of uncertainty, conflicting interests and challenges.

Similarly, SCM has been widely adopted in the field of energy planning as well, with the main goal being the optimal allocation of resources, accounting not only economic but also environmental and social criteria in some cases. So far, biofuels, biomass, hydrogen and natural gas SCs have been examined with the use of operational research tools such as modelling and optimisation, and have been evaluated with the use of emerging performance indices regarding energy consumption, technological efficiency, economic profitability and/or environmental impacts. Their evaluation has been performed either in a stage-to-stage approach, or in some cases for the entire, integrated SC, demonstrating in this way implementation possibilities that go beyond the single-stage problem.

Moreover, operational research methods and tools have proved very valuable in the design, operational analysis and optimisation of energy systems. Being met in various stages and a wide spectrum of projects, the operational research tools have become a very common practice for the solution not only of simple but also complex problems that would not have been tackled otherwise. On the other hand, the SC modelling and approach, being used for many years in the production operations management, is based on principles supporting the integrated consideration of several, often conflicting parameters.

Acknowledging the above, the aim of this research is to address the problem of planning and design of traditional SCs in the field of energy (security and planning). Accordingly, the main goal is to model such chains in an effective way and solve the emerging problems related to, with operational research tools, and, more specifically, mathematical optimisation. More precisely, in an effort to evaluate energy and fuel SCs, the scope of the present work is the development of an appropriate integrated evaluation framework, consisting of qualitative and quantitative methods and tools. Such a framework can be used for the identification and the comparative evaluation of social, environmental and economic impacts determining energy and fuel SCs presently and in the future (forecasting).

The novel approach adopted dictates consideration of the SC as an integrated system that incorporates design, planning and evaluation aspects, something not yet implemented in the field of energy SCs. To that end, by reviewing existing research carried out in the field of SCM, experience-based approaches and notions, that could be applied in the area of energy and fuel based SCs, are drawn and elaborated so as to conceive a generic representation of energy and fuel SCs. This generic representation is analysed in detail and presented together with quantitative indicators concerning the main problem parameters and the evaluation indices potentially employed in the appraisal of SCs.

Furthermore, a Multi-Objective Linear Programming model, with the extension of binary decision making (Multi-Objective Mixed Integer-Linear Programming) is developed and applied to a set of representative case studies that allow for the variation of the energy consumer features, of the resources /plants’ operational characteristics and of the time horizon that determines the problem. Decisions supported by the developed model relate to issues such energy fuel mix diversification, security of energy supply, sustainability of energy supply schemes and adaptability of the energy decision making process to incorporate emerging parameters in the problem. The focus is currently given on electricity supply but the proposed methodology, due to its generic nature, may equally apply to other types of SC problems i.e. heat and water resources energy optimisation.

So, the current work seeks to address the gap in knowledge in the management and optimisation of energy and fuel SCs. More precisely, key questions to be answered in this context consider the following:

- What is SCM and which are its fields of application in alternative energy and fuel SCs?
- Which are the alternative energy and fuel SCs (characteristics, stages, representation)?
- Which optimisation model and representation should be developed in order to simulate, model and optimise the alternative energy and fuel SCs?
- What are the sustainability/ economic/social and/or integrated criteria for evaluating these alternative energy and fuel SCs?
- What is the optimum energy and fuel SC configuration for power generation if considering technical and environmental limitations?

To this end, well-known electricity SCs are represented according to the newly introduced topology. Multidimensional issues of environmental, social and economic aspects of power planning are simultaneously dealt with under a Multi-Objective (Mixed-Integer) Linear Programming Model. Model application and results obtained are used to measure the performance of energy and fuel SCs and also designate the critical role of energy storage in cases that high RES penetration is challenged by technical constraints (such as in island grids).

Finally, what should also be pointed out is that the output of the specific work, is, apart from serving as a decision making tool, also being easily adapted to diverse SCs, locations and stakeholders' interests not only in the field of electricity but also in the broader field of energy, with only small modifications required.

The thesis structure given in the remainder of this chapter, serves for the reader to navigate along the different stages of the research work carried out. Starting from the introduction section, the evolution of the conceptualisation of the SCM and its application to energy and fuel SCs are presented, followed by the findings from the relative literature review, the innovative elements of this work and the orientation of its wide field of applicability.

After the introduction to the topic, discussed in Chapter 1, the concept of SCM is analysed in Chapter 2 by defining what is SCM, through a brief presentation of the historical evolution in the field and an analysis of the main characteristics of the SCs: stages and operations, the types of stakeholders that maybe involved, the importance of the time dimension and information sharing in the decision making, as well as the emerging issues and challenges that have driven the interest of the research community towards green, sustainable SCs. Following that and by conceiving the need for the introduction of the energy and fuel SCs notion, a complete record and analysis of the most common SCs is given. Afterwards, the current and background energy situation that has motivated the introduction of an evaluation framework for alternative energy and fuel SCs is analysed, designating the specific issues and types of decisions involved in energy and, more specifically, electricity planning.

Having illustrated the necessity for the introduction of an optimisation framework, in Chapter 3, the main optimisation methods and tools are described with regards to their characteristics and field of applicability. In addition, mathematical programming applications in the area of energy and fuel SCs are presented and classified according to the type of energy and fuel SC.

In Chapter 4 of the thesis, in an effort to identify the appropriate parameters and indices for the evaluation of alternative energy and fuel SCs, an introduction is made to basic sustainability concepts. At the same time, the key indicators that could be employed are listed.

Next, in Chapter 5, the mathematical model formulation, describing the energy planning problem is analysed with regards to its technical characteristics and limitations, alongside the equal consideration of the three sustainability objectives into a single optimisation criterion.

Subsequently, in Chapter 6, model evaluation is carried out using a set of representative case studies (isolated island communities are evaluated due to their exposure to supply insecurity and increased electricity production costs), introducing problems of different size of energy consumers, different problem-time horizon and different energy resources examined. Further details on the results is also provided by a thorough sensitivity analysis following, reflecting the main influential parameters and the importance of weights assigned in the objective function.

Finally, in Chapter 7 of the thesis, the major conclusions drawn from this research are presented together with future recommendations for the continuation and further development of the present work.

CHAPTER 2 - DEFINITION AND BASIC PARAMETERS OF ENERGY SUPPLY CHAINS (ESCS)

In this chapter an introduction to Supply Chain Management (SCM) is undertaken. The basic definitions, stages and actors will be analysed on top of the associated parameters involved in product-based SCs. Moreover, current trends and evolutions concerning more holistic considerations like Green SCM and Sustainable SCM will be analysed as well, serving as the theoretical foundations for conceiving and identifying the notion of Energy Supply Chain modelling and optimisation in the present research. In addition, a framework of analysis concerning the product-based SCs and their extension to include energy based ones will be investigated in detail, above the background issues and decisions involved in energy and fuel SCs.

2.1 Supply Chain Management

Historically, the concept of SCM and its optimisation has evolved alongside the evolution of Process SCs. A wide variety of process industries existing across Europe, has led to a large number of studies seeking to identify what processes do SCs involve, the types of decisions that are embedded and the optimisation targets under which each SC is modeled (Kondili et al., 1993, Pérez-Fortes et al., 2012, Shah, 2005, Zhou et al., 2010).

Traditionally, if considering a typical SC, one may refer to all stages and nodes involved in producing and delivering a product or a service to the end customer. To that end, it could also be described as a logistics network including order processing, purchasing, inventory control, manufacturing and distribution tasks (Yu et al., 2010). The integrated SC comprises -from an operational perspective- a set of connections, of stakeholders, all related to the production / process stages (i.e. raw material suppliers, retailers, manufacturers, distributors and end customers) which must be coordinated, controlled and satisfied simultaneously, even under conditions of uncertainty (Almansoori & Shah, 2012, Jung et al., 2004, Rodriguez et al., 2014, Ruiz-Femenia et al., 2013). It is an integrated structure of products and services that is obtained and acquired either through markets or hierarchies: making a product (through hierarchy) enhances predictability, but may require significant investment and reduce flexibility. Buying (through markets) maintains flexibility and minimises investment, but shrinks predictability (Ketchen & Giunipero, 2004). To that effect, SCs represent a sphere of actors and linkages between the market, hierarchies and customers (Figure 1), capturing the advantages, and if possibly eliminating the risks and uncertainties. They all work together in order to improve the overall performance and efficiency and also to provide more competitive and more sustainable products and services. SCM is an important approach and tool for any type of firm, company and/or organisation since it is about applying a total – integrated system approach in order to control and manage the flow of information, materials and services in the side of the customer demand fulfillment (Zhang, 2008).

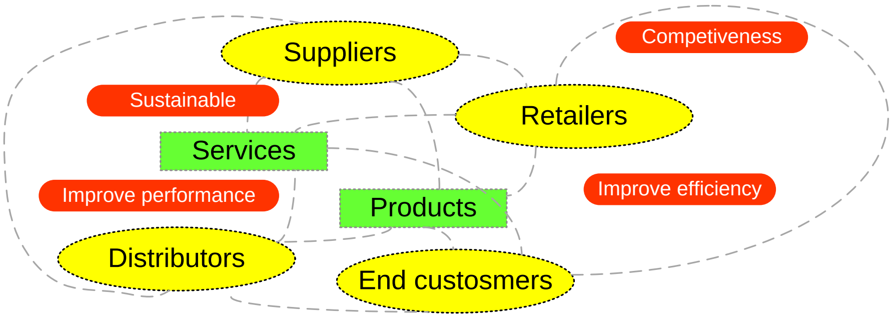


Figure 1: The operational environment of a SC

It is very interesting to note that SCM definitions are dependent on the type of information being exchanged at each level of examination. Some basic/descriptive definitions of SCM are given below, reflecting upon the characterisation and identification of similarities between energy and fuel SCs that will be described in the following section.

"Supply chain management is the coordination of production, inventory, location, and transportation among the participants in a supply chain to achieve the best mix of responsiveness and efficiency for the market being served" (Hugos, 2003).

"SCM is the chain linking each element of the manufacturing and supply process from raw materials through to the end user, encompassing several organisational boundaries" (Tan, 2001).

"SCM is the integration of the various functional areas within an organisation to enhance the flow of goods from immediate strategic suppliers through manufacturing and distribution chain to the end user" (Tan, 2001).

"SCM emerges from the transportation and logistics literature of the wholesaling and retailing industry, emphasizing the importance of physical distribution and integrated logistics" (Tan, 2001).

"SCM is the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole" as cited by Hugos (2003) after the work of *Mentzer et al. (2001).*

"*SCM is the management of material, information and capital flows as well as cooperation among companies and vectors along the supply chain"* (Mentzer et al., 2001).

Therefore, if all the above definitions could be included in an integrated concept, one may identify a management which encompasses organisational boundaries and links from various functional areas and suppliers to the end customers, under an integrated logistics network. It must also be noted that SCs equally involve, in terms of significance, both external and internal impact factors based on the specific goal of each organisation: SC internal optimisation accounts for better organisation, more efficient production processes etc., all these being defined by each system's boundaries, whilst SC external environment considers customer demand-driven decisions i.e. for a more economic or more efficient end product. These environments are actually interrelated and sometimes these external forces are so decisive, that they can push towards an internal change and restructuring of the SC.

In the following section, a framework of analysis of SCs concerning both the internal and external implications is presented, serving as the theoretical foundation of ESCs conceptualisation, a notion to be introduced by the present work. This framework includes SC stages, operations, stakeholders, information sharing and, on top of all, the time dimension (horizon) of decision making (Figure 2).

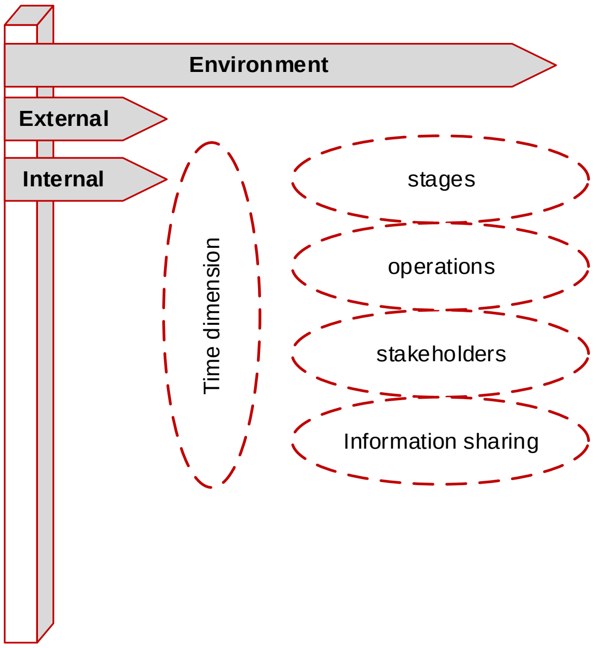


Figure 2: The framework of analysis

2.2 SC stages and operations

Drawing information from recent research studies, emphasizing on how the supply system can be predicted, controlled and optimised (Caniëls & Romijn, 2008) so as to successfully deal with possibly appearing significant uncertainties and simultaneous meet conflicting needs, the main, typical structure of a SC comprises (Figure 3):

- Raw material, feedstock production (supply side) - (inventory-storage)
- Distribution / logistics (of raw materials)
- Manufacturing / production process (inventory-storage)
- Distribution /logistics (of the end product)
- The demand side (consumption)
- End-of-life (management)

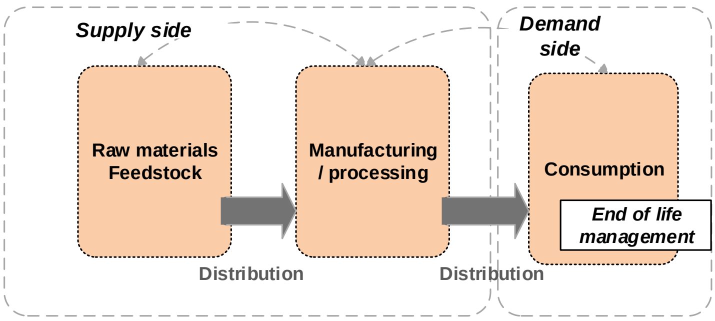


Figure 3: Typical structure of a product-based SC

In these stages the operations undertaken (Hugos, 2003) may in general fall under the four following categories:

- **Plan**: this is about planning and organising all the operations involved the integrated SC network.
- **Source**: this includes all the operations necessary so that the appropriate feedstock in each production stage is ensured. The goal is to have efficient operation across the entire SC.
- **Make**: this is about the operations of the SC that produce the different products across the SC. It includes product design, production and facility management.
- **Deliver**: this encompasses the sets of activities fulfilling the products', intermediate or final ones, distribution and delivery. It provides the core connections among different nodes in the SC logistics network.

2.3 SC stakeholder identification and satisfaction

According to Parmar et al. (2010), the term "stakeholder" first appeared in an internal memorandum at the Stanford Research Institute (now SRI International, Inc.), in 1963. The term meant to describe that *“stockholders are the only group to whom management needs be responsive”*. During the 70’s and the 80’s the term evolved on the side of explaining management problems that involved high levels of uncertainty and change. The identification of stakeholders from the SC point of view is actually an assessment of the key players and their roles and interests across it. A typical list of stakeholders includes employees, owners, suppliers, manufacturers, distributors, importers and exporters. Given the level of interference in the SC (being part either of the internal or the external environment), they are characterised accordingly (internal and external stakeholders). To this end, the stakeholder analysis contributes to strategic SC design by identifying the appropriate forms of stakeholders’ participation, whilst acknowledging the degree of potential risk, satisfaction and prioritisation that may apply to each one. Thus, it is more than obvious that to formulate coherent strategic plans and SC design and operation, the identification of stakeholders is of primary importance (Freeman, 1984).

In this context, if transforming Figure 3 to also consider of stakeholders and interested parties being involved, directly or indirectly, a simple illustration can be provided by Figure 4.

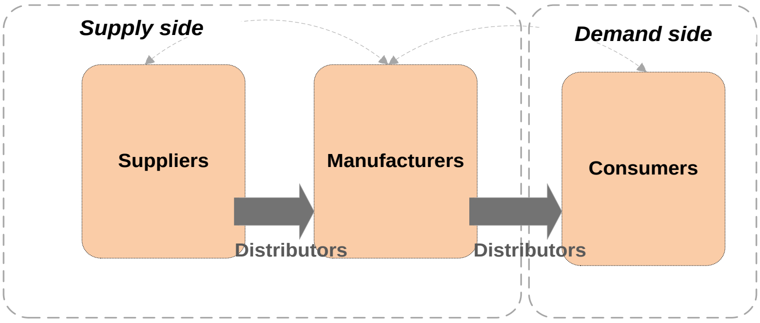


Figure 4: Product-based SC considering stakeholders' involvement

2.4 Information sharing

In an SC network, information sharing across different layers and stakeholders supports the organisation and time scheduling of daily/immediate activities being the key SC operational drivers: how much to produce, store, allocate and distribute to the end customers.

Each market / end customer group has different needs, response times and orientation. Some SCs are oriented on the basis of efficiency, others on response time, and others on both (Hugos, 2003). On top of that, of critical importance -on the basis of responsiveness and efficiency of the integrated SC network- is to efficiently predict future demand and needs so as to quickly adapt to constantly changing requirements.

At this point, it becomes apparent that the time frame is very important. For example, if we are considering of a typical product i.e. a food product, the market needs to have a monthly or even an annual demand basis differentiation, whilst if we are considering of energy, and more specifically of an electricity SC, the response time may refer to an hourly-based time step.

Typically -owing possibly to simplicity reasons and the lack of integrated control-management– the flow of information follows a bilateral model of interaction called monolayer information flow i.e. between the retailer and the distributor, or between the distributor and the manufacturer, or finally between the manufacturer and the supplier, each one being responsible for the delivered product in his micro-scale, with a small stall potentially causing a domino effect (Zhang, 2008).

However more complicated SCs, like energy and fuel SCs (that will be defined later) require holistic control, using multilayer information flows which enable participation of any stakeholder at any stage of the SC. To this end, more complex distributions and logistics functions have been gradually introduced since the 90's that have under the umbrella of SCM facilitated the competiveness and further evolution of the sector (Tan, 2001).

Each stage of the SC contains certain information concerning energy and material flows. So the type of information related to the nodes/stages of the SC is critical to the design and operation of any product and/or energy and/or fuel SC and it is more effective on the basis of multilayer *vs* monolayer information exchange (Figure 5).

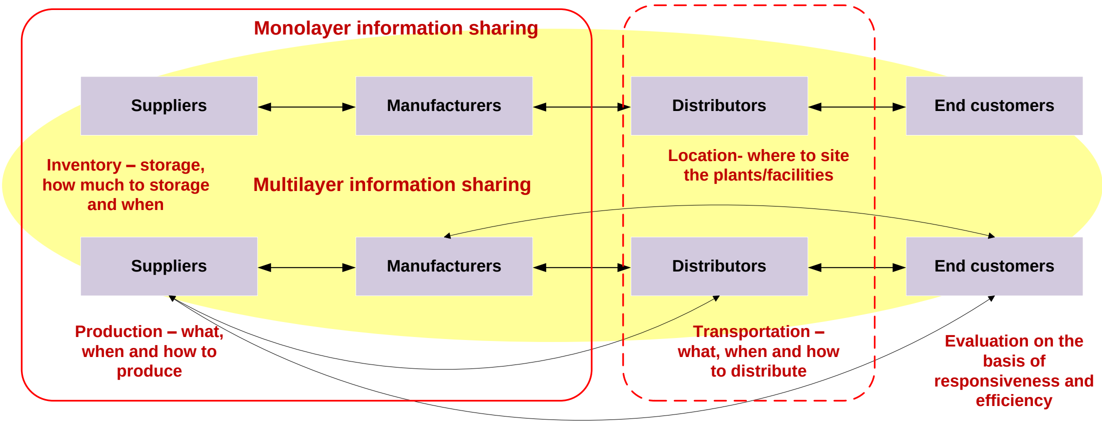


Figure 5: Information sharing in SC under the conceptualisation of (Hugos, 2003) and (Zhang, 2008).

The need for multi-layer information exchange is critical in complicated structures of energy and fuel SCs, since in each SC, multiple levels of stakeholders' involvement are present, denoting the demanding nature of the SC features. This is something to be discussed thoroughly in the analysis of energy and fuel SCs. That demanding and conflicting nature is also the one introducing additional dimensions and concepts in SCs, such as the Green SC.

All these parameters are mainly dimensions of SCM from the operational point of view. However, many decisions have to consider a longer time-perspective, under the view of strategic management. Very specific characteristics of these types of decisions that require good insight concern "identifying, explaining and predicting" the determinants of organisational performance (Ketchen & Giunipero, 2004).

2.5 Time dimension

SCM decisions are mainly defined by the time dimension involved in each decision. More precisely, one can designate strategic (Supply Chain Design), tactical (planning), and operational (Thery & Zarate, 2009) aspects (Figure 6). Under "strategic" we have the selection of capacity and location of new plants, warehouses and / or expansion of existing ones; under tactical we have selection of logistics, type of products as well as transportation modes, and finally under operational decisions fall the material flows, production and day-to-day scheduling (Figure 7).

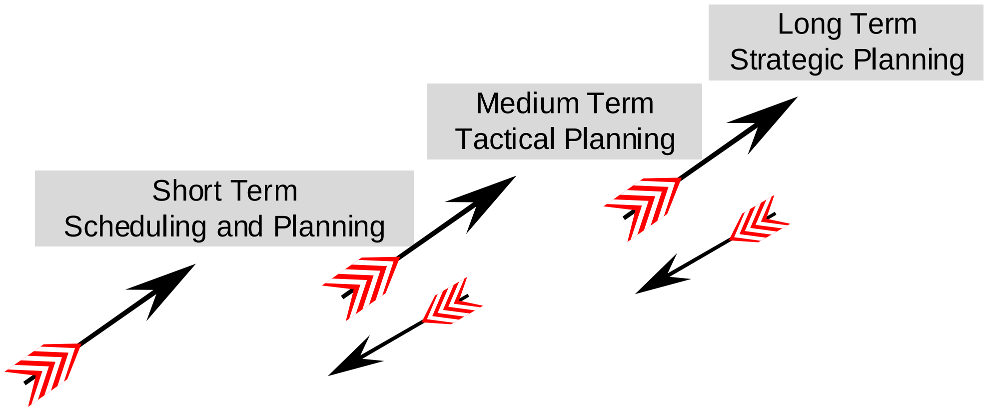


Figure 6: Different time frames in SCM planning

2.5.1 Strategic planning and decisions (horizon of several years)

Strategic planning deals with decision making that has long-term and significant implications on the business and/or any organisational structure of the SC. It may involve substantial alterations from design and configuration practices followed up to date. These types of decisions may include selection of capacity and location of new plants, warehouses and/or expansion of existing ones, procurement and production choices. Generally these decisions may be classified according to (Manzini et al., 2011) as related to:

- Capacity
- Inventory
- Procurement
- Production

In general, strategic decisions follow an unstructured form (they have very specific limitations and boundaries). To that end, the problem environment and the respective affecting factors must be identified and assessed, accounting for the uncertain environment, their dynamic nature and the causal relationships created between, altogether eliminating the risk of fail of each decision.

2.5.2 Tactical decisions (horizon 1-15 years, period: year)

Tactical planning involves decisions that are linked to the implementation of strategic ones. They are mainly of medium-to-shorter character. Decisions like the best echelon inventory configuration i.e. development of distribution channels on top of all types of resources' workflows are established.

2.5.3 Operational decisions (horizon 1 year, period: day, week, month)

The operational decisions, mainly applied in product-based SCs, are mostly short-term ones and they are carried out even at a day-to-day repetitive time plan. Vehicle routing, shipments' planning, materials' requirements and scheduling, customers' satisfaction, etc. Operational decisions are taken at lower levels of the decision-making pyramid and are more of executive nature: all the information is focused on the process of managerial decision making.

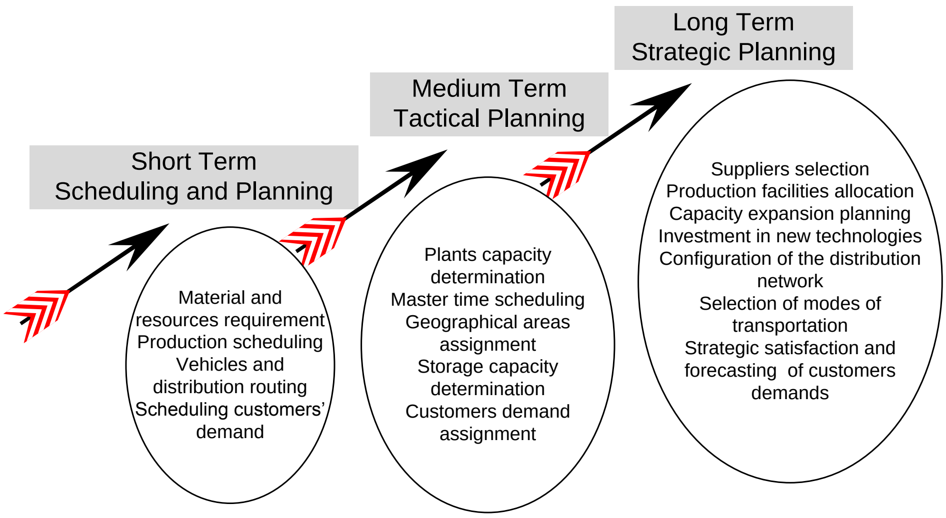


Figure 7: Types of decisions in SCM according to the stage and time frame selected; after the work of (Manzini & Bindi, 2009)

2.6 Emerging Research Issues and Challenges on Modern and Future Supply Chains

2.6.1 Green and Sustainable Supply Chain Management (GSCM)

In the 50's and the 60's, most manufacturers emphasised on mass production to minimise unit production costs as the primary operation strategy, with little product or process flexibility. However, nowadays much pressure has been put on integrating “environmental thinking” into SCM, including design, material selection, production process, delivery and distribution of end product to the customer, as well as post consideration -end-of- life- of the product after its useful lifetime (Hoejmose et al.,2012).

Therefore, the concept of Green Supply Chain Management (GSCM) was introduced, which is the kind of management model that considers the environmental influence and efficiency, by involving suppliers, manufacturers, sellers and consumers.

Many studies have been conducted on the specific area, primarily on the identification of motives, pressures and barriers to the adoption of GSCM. As quoted by Diabat & Govindan (2011), and Zsidisin & Siferd earlier (2001), who provided primary definitions of GSCM, “*GSCM is the set of supply chain management policies held, actions taken and relationships formed in response to concerns related to the natural environment with regard to the design, acquisition, production, distribution, use, re-use and disposal of the firm's goods and services*”.

However, the transition from conventional to green and environmentally conscious SCs (Giarola et al., 2012, Ruiz-Femenia et al., 2013, Srivastava, 2007) is hindered by many obstacles. These barriers as identified by Jayant & Azhar, (2014) include knowledge-based factors like lack of awareness about the positive impacts of reverse logistics, lack of corporate social responsibility, lack of environmental awareness on both, the supply side and the demand side, cost and technological implications (such as alterations), fear of failure and resistance to technological adaptation. These barriers must be gradually assessed considering that key aspects of GSCM should incorporate:

- Total quality management
- Reverse logistics
- Life Cycle assessment
- Product management
- Obligation to rules and regulations
- Proactive environment behavior and insights

In general, GSCM is a totally internal procedure that sometimes needs major restructuring and very good knowledge of organisation procedures and practices. Independent of the type of business (Business-to-Customer, or Business-to-Business (B2C or B2B)), consumer awareness is critical and relative incentives must be prioritised in the SCM. All these parameters, being regulated under an environment of external stakeholders that are institutionally oriented, are pushing towards a reactive change (Figure 8), whilst the internal environment of the SC proactively tries to meet future challenges and goals.

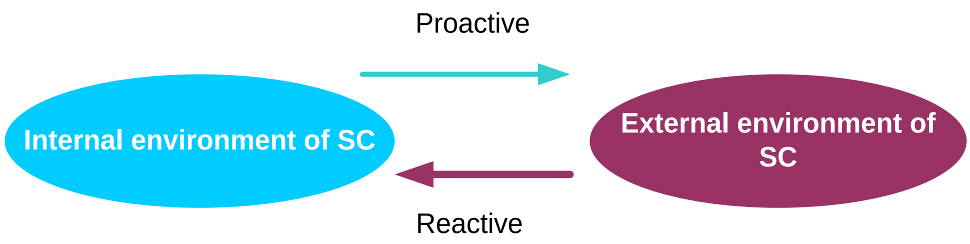


Figure 8: Proactive and reactive behavior in SCs

GSCM basic principle is getting more attention lately, as a sustainable development model for modern enterprises and as a vital part of Corporate Social Responsibility (CSR) strategy. GSCM goals and best practices include:

- Align green SC goals with business goals
- Evaluate the SC as a single life cycle system
- Use GSC analysis as a catalyst for innovation
- Focus on resource reduction to reduce waste

Responsive actors and stakeholders as well as proactive institutions and regulations, along with appropriate customer engagement make environmental responsibility of equal importance to CSR. To that end, many companies are re-designing/ reconsidering their SCs under very specific optimisation goals as:

- Technical efficiency
- Economic viability
- Environmental performance
- Energy minimisation
- Waste impact mitigation
- Ecological footprint
- Cradle to grave or even upcycling considerations

All these optimisation goals need to be applied at every stage of an SC under planning. Through the years, special focus has also been put on the identification of the characteristics of the business sustainability with emphasis on the stakeholders' interests as well as on environmental, social and economic issues. On top of that, similar to product-based SCs, energy and fuel SCs' conceptualisation has been developed under the same principles in response to emerging complexities and sustainability pressures, driven by techno-economical drivers.

2.6.2 Sustainable SCM

Sustainable development is a global challenge that each community, country, firm and individual has to respond to. With the use of treaties and agreements, at least at the level of countries, considerable ground has been covered in the field of environmental protection. However, sustainability as a notion must be integrated in each activity, following the basic three pillars (i.e., economic, environmental, social) with a long-term focus on achieving a global optimum level of acceptance.

According to the Brundtland report, "*sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (World Commission on Environment and Development, 1987). Further on sustainable development, as Ahi & Searcy, (2013) refer to, Sustainable SCM (SSCM) derives from the integration of Business and Corporate Sustainability with SCM. Some basic definitions of SSCM following provide evidence on their argument:

As Singh et al., (2009) analyse, after the review work of Seuring & Müller, (2008):
"*The integration of sustainable development and supply chain management [in which] by merging these two concepts, environmental and social aspects along the supply chain have to be taken into account, thereby avoiding related problems, but also looking at more sustainable products and processes*".

As Singh et al., (2009) point out, after the review work of Closs et al., (2010):
"*Reflection of the firm's ability to plan for, mitigate, detect, respond to, and recover from potential global risks. Risks involving substantial marketing and supply chain considerations include product development, channel selection, market decisions, sourcing, manufacturing complexity, transportation, government and industry regulation, resource availability, talent management, alternative energy platforms, and security*".

Typically, in the product-based SC special focus of attention is (Hillier, 2010): a) in the design that is sensible to the environment b) in the efficiency improvement and c) in the recovery (Figure 9). Integrated approaches like life-cycle assessment and "cradle-to-grave" have been incorporated in the resource management driving towards waste prevention and control, responsible-care towards natural resources utilisation and waste impacts (air emissions, water wastes etc.), seeking for continuous improvement of the overall performance of the SC.

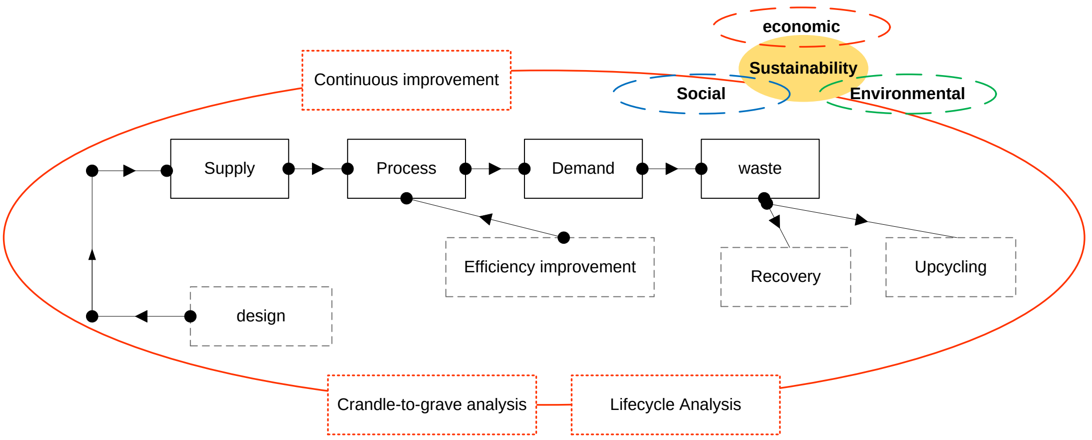


Figure 9: SCM and integration of the sustainable and green dimensions; after the work of (Lam et al., 2015)

These new issues have to meet the challenges (Singh et al., 2009) of building a comprehensive SC in terms of:

- Design and effective coordination of the re-designed SC (including products, stages, operations and services along with their interaction with stakeholders)
- Creation of economic and effective reuse/recycling practices
- Identification of new markets and business models that can support the newly designed SCs
- Identification of the drivers for change.

In addition, the outsourcing of SCs as well as their increasingly globalised character, with numerous customers (companies), producers, distributors and products, up and downstream, has developed an extended level of complexity, assigning a great degree of difficulty in supply, process and demand management of the SCs (Kovács, 2008). To that end, and seeking for a more quantifiable record of progress, specific metrics have been assigned as performance measures towards changes. This aspect will be further analysed in detail in Chapter 4, with special focus on ESCs.

2.6.3 Energy supply chain and planning

In recent years, significant efforts have been made to increase the share of Renewable Energy Sources (RES) mainly in the electricity sector, and to provide overall economically viable solutions for the available technological options. Fossil based energy sources, mainly oil and coal, seem to be gradually either abandoned or replaced by RES, or trying to be more efficiently exploited by the introduction of advanced and clean technologies.

However, harvesting RES, which do not require the acquisition of the raw material for power, heat and/or fuel production is challenging if also accounting for the mandates for Greenhouse Gases (GHGs) emissions' reduction at all levels of planning (either at a country level, and/or European, - continent level, even at the level of global, world-wide scale). These issues have triggered the assessment of RES penetration under a different perspective, a more integrated and sustainable one. Energy and electricity to a greater extent include decisions to be undertaken under different time-frames, for different types of customers accounting for sets of technological options. Traditionally, the goal of fully meeting the demand was eliminated to provide the most efficient energy and power supply option in terms of economic feasibility and security of supply.

Classic market based instruments, regulated under the provision of supply and demand, seem to gradually become inefficient, because the toolbox provided (regulations, investment and financing funds, specific customers prioritisation) cannot meet the current complexities of energy planning: simultaneous consideration for environmental and social implications on top of techno-economic ones, under a wide spectrum of different types of stakeholders to be satisfied.

Energy design, operation and planning involves a wide set of decision actors, resources and processes that need to be, first of all identified and, on a second basis, appropriately controlled. The major decisions that are investigated by the SCM application include product efficient production and delivery to end customers, optimisation and restructuring of the existing or new logistics networks, capacity planning and/or expansion of existing ones, optimal selection of the end customers and prioritisation of the available supply options.

In complete accordance with Process SCs, the conceptualisation of SCM was equally applied to the field of renewable and fossil based energy and fuels SCs. Following the close and strong example of petroleum SCs, on the side of fossils and biomass to heat, power and transportation on the side of RES, fossil and renewable energy and fuel SCs have been designed, optimised and studied under that concept.

Energy and fuel SCs nomenclature may be characterised by two basic factors / attributes and/or a combination of them:

- By the raw material/ feedstock source of energy that they “harvest” to produce/ manufacture the ‘end product”
- According to the type of material; -energy - fuels that flow through the stages.

Following that, the subsequent energy and fuel SCs are identified:

- Biomass-to- (heat, power, fuel) SC
- Coal-to- power SC
- Geothermal -to- (power, heat) SC
- Hydrogen -to- (power, fuel) SC
- Hydro -to- power SC
- Natural gas -to- (power / transportation fuel, heat) SC
- Oil -to- (heat, power and fuel) SC
- Solar-to- (power, heat) SC
- Wind -to- power SC

Some broader characterisation of SC groups could follow the end use / product delivered, i.e.:

- Power (electricity) SCs
- Heat SCs

- Fuel (Transportation) SCs.

In order to get a better understanding of the concept of ESCs and their similarities to product-based SCs their stages, operations and stakeholders are analysed in the following section (Chapter 2.7).

2.7 Basic characteristics of the ESCs

2.7.1 SC stages and operations

In general, the typical product and process-based SC stages and operations may equally well apply to energy and fuels SCs (Figure 10). So, under the product-based structure, they may be moderated as:

- Raw material, feedstock production (supply side) - (inventory-storage)→ primary energy and /or fuel supply
- Distribution / logistics (of energy and/or fuels)
- Manufacturing / production process (inventory-storage)→ conversion to heat and/or power and/or fuels
- Distribution /logistics (of the end product)→ distribution of heat and fuel and transmission in the case of power supply
- The demand side (consumption)

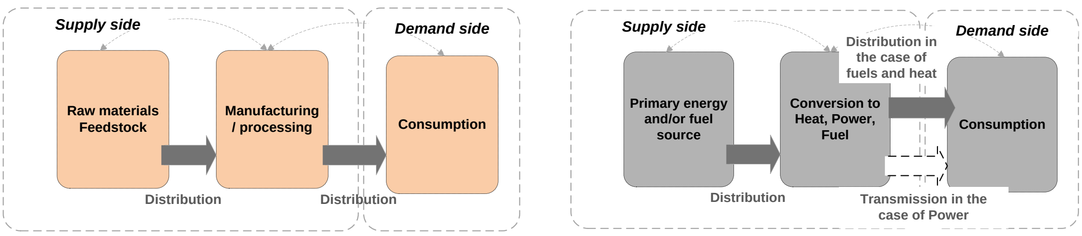


Figure 10: Configuration and stages in ESCs (compared to product based)

More precisely in the SC one may identify all renewable and fossil-based energy resources like coal, petroleum (oil), natural gas, uranium, biomass, geothermal, wind, wave, hydro and solar energy, as well as energy carriers like hydrogen. In the process/conversion stage one may find all the possible conversion technologies from fossil and RES-based resources to heat, power and fuels like gasification, combustion, transterification (some of them with a very wide field of fuel and energy applicability).

In addition, one may integrate also emerging technologies, such as oscillating water columns for wave-to-power, other types of turbines and finally energy storage technologies (e.g., solid state batteries, compressed air systems, pumped hydro technologies etc). At the final stage of consumption, as already mentioned, the characterisation does not only follow the type of consumer, but in its generic form the type of energy delivered to the end consumer (heat, power and/or fuel) (Figure 11).

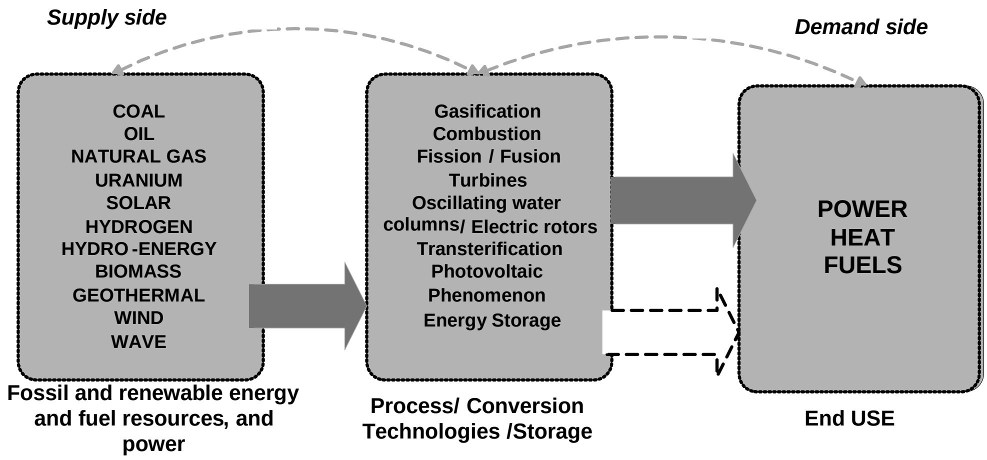


Figure 11: Energy and fuel SCs

As the set of the available resources and fuels along the process and conversion technologies to end product constitute a quite wide set of options, in the present work electricity SCs are chosen to be analysed in detail. Power SCs, in terms of sources - conversion - products/ energy end use, integrate in their majority the widest combination of all of already known, raw materials- feedstock/ energy sources/ that are converted through multiple process-conversion pathways to electrical power. To that end in Chapters 2.7.5-2.7.12, the most commonly met energy and fuel SCs will be presented, with special focus given on their conversion to power. Reference will also be made to the role of energy storage and interconnection as specific elements of the design of electricity SCs.

2.7.2 SC stakeholder's identification and satisfaction

Whilst in the product-based SCs the stakeholders can be identified within the internal environment among the customers, suppliers, distributors and final consumers, in the field of energy supply, as each project results to a wider impact, either positive and /or negative in the area applied, the population involved includes all the elements of a contemporary society. To that end one may identify the following groups of stakeholders (Figure 12):

- Investors
- Raw materials /Fuel suppliers
- Technology and equipment developers and suppliers

- Competitors
- Local authorities and government
- Public providing services
- Local population and society
- Media / information population
- Scientific society and non-profit organisations (i.e. NGOs)
- Labour unions and associations
- Consumers' advocates

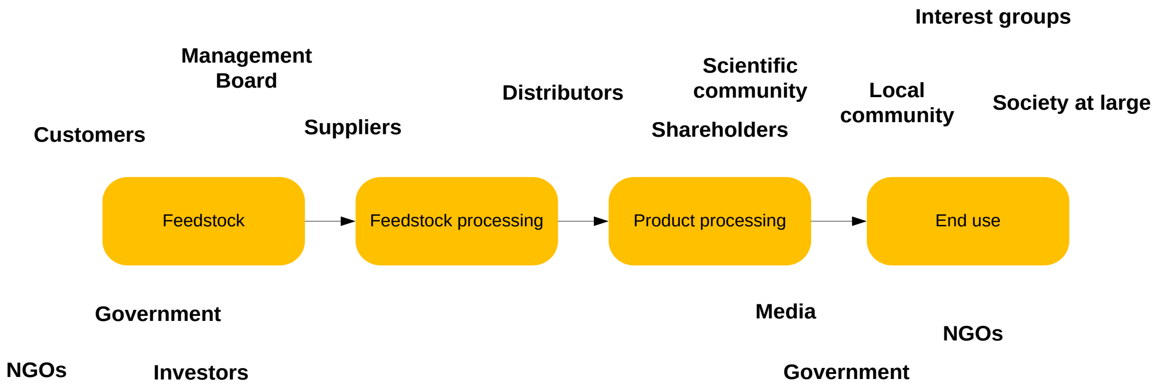


Figure 12: Types of stakeholders involved in the energy and fuel SCs

Additionally, depending on the level of examination of these ESCs, either from the bottom-up perspective (the customer/consumer) or from the top-down perspective (government, society, and community-level), one may identify either governmental organisational structures and legislation or system operators. Especially for case studies in the Greek context (analysed in this thesis), one can recognise the Public Power Corporation S.A. (PPC) as the biggest power producer and electricity supply company in Greece, the IPTO S.A. (Independent Power Transmission Operator S.A.) and the HEDNO S.A. (Hellenic Electricity Distribution Network Operator S.A.) for the electricity SC. IPTO S.A. is responsible for the management, operation, maintenance and development of the Hellenic Electricity Transmission System and its interconnections, while HEDNO S.A. is responsible for the management, operation, development and maintenance of the Hellenic Electricity Distribution Network. In the field of natural gas supply DESFA (National Natural Gas System Operator (DESFA) S.A. is responsible for the operation, management, exploitation and development of the National Natural Gas System (NNGS), and its interconnections, in order for the NNGS to be economically efficient, technically sound and integral and to serve the needs of the Natural Gas Users in a safe, adequate, reliable and economically efficient way.

2.7.3 Information sharing

Information sharing in energy and fuel SCs follows not only the multilayer approach but actually a two-dimensional space: there is not only information sharing between customers, producers, suppliers and manufactures (horizontal approach), but also through a top-down and bottom-up channel depending on the level of decision making (Figure 13).

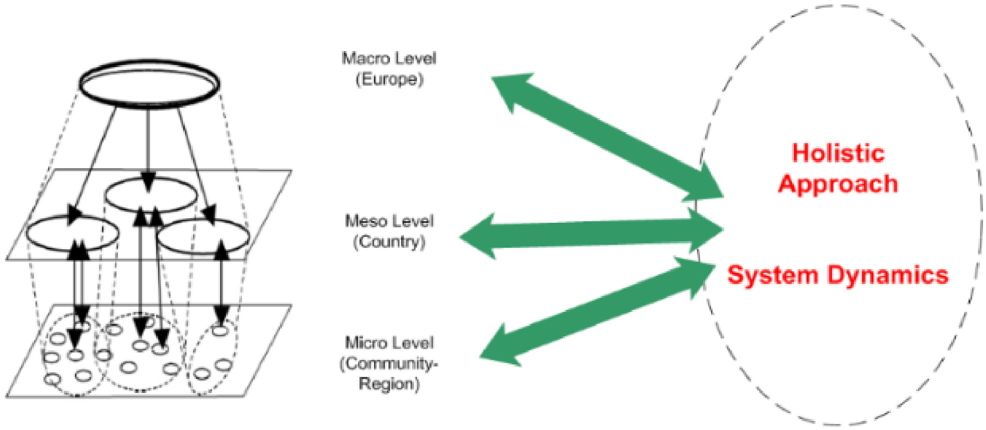


Figure 13: Multi-level involvement of stakeholders in a SC network

Moreover, one may point out an 3rd dimensional information space that incorporates sustainability issues and parameters (environmental and social) which must be identified in order to be communicated to the design and operation of the SCs (Figure 14). These must be equally addressed to all the processes and stages of the SC i.e. land use, sustainability issues, water and raw materials utilisation, under sustainability constraints, resources' consumption, demand /end consumer, prioritisation issues, and social impact efficiency of the end product.

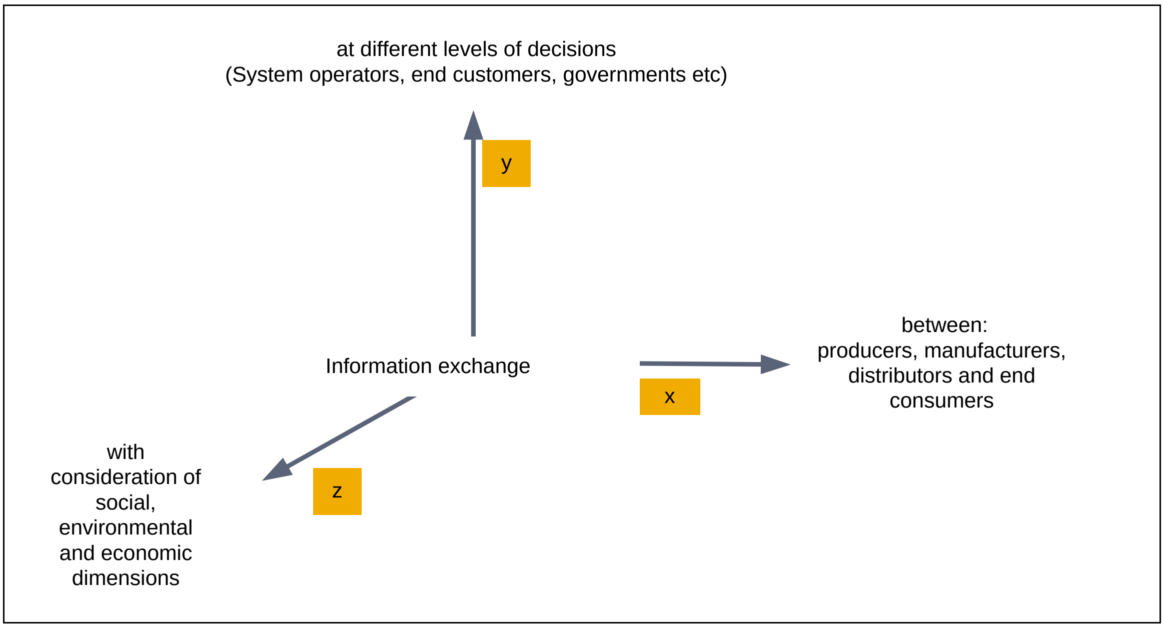


Figure 14: The different dimensions of information sharing in energy and fuel SCs

2.7.4 Time dimension

Time dimension is very particular to energy and fuel SCs. In complete similarity with product-based SCs, energy planning involves all three dimensions of strategic tactical and operational decisions, as analysed above. In the present work to prove the adaptive nature of the modelling approach to both different types of fuels and time scales, both a strategic and an operational problem of electricity SC for an isolated (small scale) consumer and a larger one (with a wide set of available energy supply option on top of the interconnection alternative) will be investigated. Types of decisions and specific problems that are examined include: optimal fuel mix determination in terms of social, environmental and techno-economic implications in the case of the operational (level) problems, creation of new plants and/or expansion of existing energy infrastructures, and investment in storage or non-storage solutions (exploitation of interconnection). All these, will be analysed in further detail in the problem definition chapter (see Chapter 5). In the following section (Chapters 2.7.5-2.7.12) the major fossil- and renewable-based SCs will be shortly presented.

2.7.5 Biomass and Biofuels SCs

The biomass and more specifically the biomass-derived energy (bioenergy) is renewable energy coming from any organic material from plants or animals. Sources converted to bioenergy include a wide range of feedstock from diverse origins (like agricultural and forestry residues, municipal solid wastes, industrial wastes, and terrestrial and aquatic crops grown solely for energy purposes (Bauen et al., 2009)). Additionally, according to the different end energy uses i.e. heat, power (electricity) generation or transportation, specific terminology applies to biomass. However, in the general case biomass characterisation follows two key principles:

- the supply side (which types of raw materials are used) and
- the demand side (in which type of end – product/ energy it is transformed)

Exceptionally for biofuels, categorisation to 1st, 2nd, 3rd and 4th generation is a bilateral resolution between feedstock and the processing technology.

As one may note from the following illustration (Figure 15) three major process technologies are employed to biomass energy conversion: thermo-chemical (combustion, pyrolysis, and gasification), bio-chemical (digestion and fermentation) and mechanical extraction with transesterification (McKendry, 2002a). The selection criterion of the raw material and accordingly of the end product is the moisture content of the biomass i.e. sugar cane (which has high moisture content) which requires an aqueous conversion like fermentation to lead to biofuels. Dry biomass such as wood is more economically suitable for pyrolysis; finally, gasification is suitable for heat and power (McKendry, 2002b). Usually bioenergy refers either to energy systems that produce heat and/or electricity while biofuels refer to liquid fuels for transportation (Figures 15, 16).

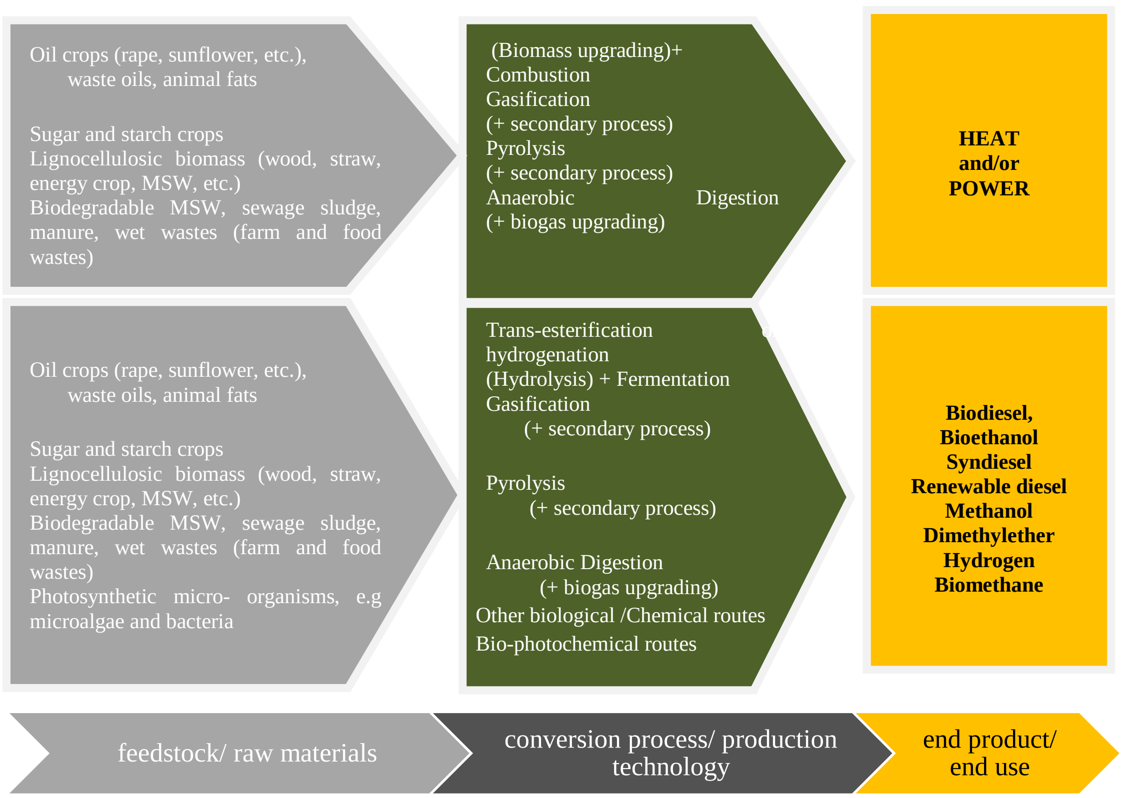


Figure 15: Biomass conversion routes (Papapostolou et al., 2011a)

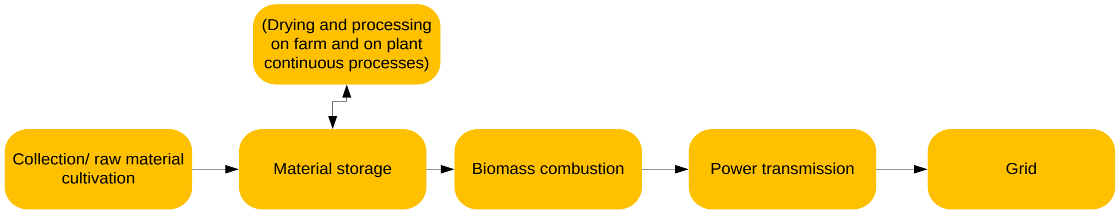


Figure 16: Biomass to heat SC; after the concept of (Dunnett et al., 2007)

A biofuels’ production (chain) involves many sub-domains such as agriculture (energy crops, raw materials production), biofuels' production procedure itself (transformation of already existing plants or/and implementation of new ones) and of course it also involves the integrated supply and trade network. In its typical form it usually incorporates the following activities or stages (Figure 17):

- Raw materials production (which is related to the land availability and suitability, soil’s efficiency associated to different types of plants)
- Biofuels' production (which refers to the transformation of raw materials through various processes into biofuels)
- Blending (in the case that biofuels are provided to the end consumers in mixed state)
- Biofuels’ supply- transportation and finally
- Consumption

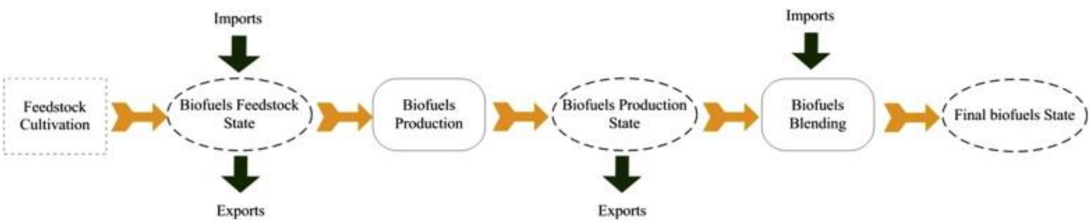


Figure 17: The biofuels’ SC (Papapostolou et al., 2011a)

The particularity and the specific interest in this SC is that it is possible, in any stage of the SC, for sub-products to be exported due to over adequacy or economic profitability. The decision point, i.e. in which stage of the SC an investor is going to step in, is a strategic decision for the development of biofuels’ market and it is determined by multiple technical and financial parameters. In any case it does not pose the question whether a country has the possibility in terms of financial and technical potential to become a biofuels' producer or not, or it has to import the required quantities. So a range of decision is to be met.

More precisely, goals and issues under consideration are:

Goals

- Selection of raw materials
- Selection of geographical areas/ sites
- Conversion/ efficiency constraints
- Capacity of the production plant
- Capacity of the storage facilities
- Satisfaction of the demand
- Imports/ exports
- Economics

Issues

- Raw materials
- Transportation/ distribution costs
- Production costs
- Operation and maintenance costs
- Imports/ exports
- Incomes from end product selling

2.7.6 Wind SCs

Wind energy and more specifically wind energy harvesting has its origins in the ancient years – from wind mills in isolated farms to pumping water and to generating electric power with vertical axis wind machines; "*windmills being met at the Persian-Afghan borders around 200 BC and the horizontal-axis windmills of the Netherlands and the Mediterranean following much later (1300e1875 AD)*" (Kadellis & Zafirakis, 2011). Wind and solar SCs following the mandates of energy business, have the particularity of being characterised as "A make-to-order industry". It is a power production industry completely adjustable and flexible to end customers' demand, with sizing and technical characteristics allowed to adapt to the order requested.

In contrast to all other ESCs, partly due to the dispersed character of the resource and the idea of providing more unique – single solutions to collective ones like coal SCs, the research in the field of these SCs has mainly focused on optimising the developers – manufacturers and operators and on the coordination of this network, since it is capital intensive and risky (Figure 18). At the same time, it is important to mention that opposite to other SCs, the energy source is completely outside the control of the operators: wind cannot be controlled (other than curtailing wind turbines – so you can reduce power conversion but you cannot increase power conversion if demand increases).

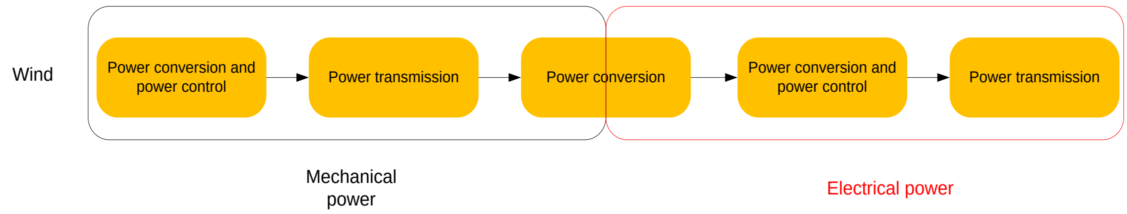


Figure 18: The wind energy SC

Despite this downside, and owing that to a wide range of environmental benefits of wind energy, along with its significant energy yield, its applications either in a wide scale, - wind parks- or in small dedicate ones – wind turbines for single customers- wind SCs are very interesting to be examined in the present investigation.

2.7.7 Solar SCs

Solar energy is a widely used RES with its characteristics being its abundance and equal dispersion for the biggest part of the planet. Unlike other renewable sources, the relatively "predictive" nature of supply (compared to wind), has rendered solar energy suitable, especially in the tropical countries, where solar irradiance average annual sum reaches approximately 2200 kWh/m^2. Its final uses mainly comprise heat and power, not only at national, regional or residential level, but also at an individual level, with small applications reaching and fulfilling daily demand. A solar electric system starts from the photovoltaic (PV) material (Figure 19) and ends to the Grid. PV material most commonly refers to silica semiconductor material, though there are other types. The semiconductor material is manufactured in the form cells, and these cells are used to generate electricity whenever photons (sunlight) strike the PV material and cause electrons to move.

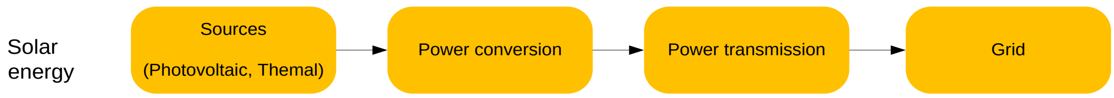


Figure 19: The solar-to-power SC

2.7.8 Hydro-energy SCs

Hydro-energy is one of the most mature RES used for electricity generation, contributing significantly to the worldwide electricity consumption. The corresponding facilities are called hydroelectric powerplants, and hydropower is generated when the water falls by the force of gravity, so its stored potential energy – due to its elevation in the dam- is transformed into kinetic energy. Afterwards, the kinetic power of the water is turned into mechanical power in the turbine (Figure 20). The turbine turns the generator rotor which then converts this mechanical energy into electricity. The term energy SC is not commonly applicable in hydropower: its operation is based on the model "on demand energy", because such plants are normally introduced whenever there is a peak load deficit in the electricity balance/demand.

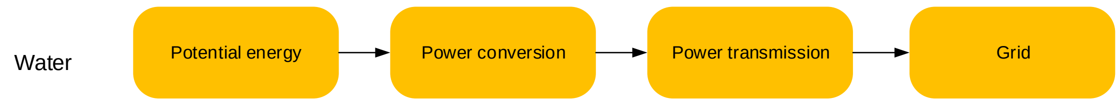


Figure 20: The Hydro-energy SC

2.7.9 Geothermal energy SCs

Geothermal energy refers to the thermal energy being stored between the earth's surface and a specified depth in the crust. The heat can be converted into other energy forms in accordance with the depth of the geothermal reservoir and its potential to support various usage purposes. Heat-pump systems can be used to exploit geothermal energy. With electricity generation also being used in case of appreciating high-enthalpy geothermal fields. To this end, the concept of energy SC only refers to the extended distribution network of geothermy (Figure 21).

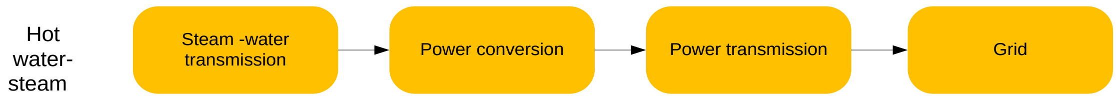


Figure 21: The geothermal - energy SC

2.7.10 Coal SCs

The coal SCs, dedicated from early years to power production, is an SC similar to the one of biomass and biofuels where upstream is raw material and not energy, and has very specific and pre-set stages, following its production process. So one may identify: Mining, preparation, transportation to coal power plant, power production and power transmission (Figure 22). In some case storage is also applicable either at power plant and/or upstream.

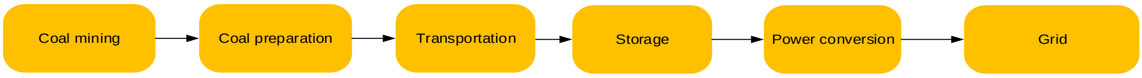


Figure 22: The coal-to-power SC

2.7.11 Natural Gas and Oil SCs

Oil and natural gas energy SCs (Figure 23) are almost identical, presenting the same raw material production, the same transportation and aggregation storage, similar refinement and processing and most importantly the same end uses (heat, power fuels). In the occasion of conversion to power, nowadays most plants which run under oil combustion engines have been replaced by gas turbines. In any case, research around these SCs presents special interest on how to improve associated benchmarks.

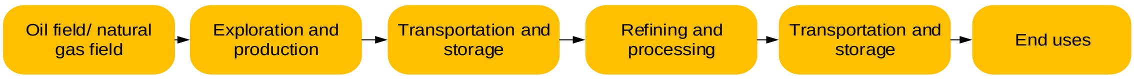


Figure 23: The Natural Gas and Oil SCs

2.7.12 Hydrogen SC

Often referred as an “energy vector” or “energy carrier”, hydrogen is a source of energy that in contrast to more conventional energy sources, cannot be mined but is used as a mean of transporting energy from one place to another. Its attributes are very similar to electricity which carries energy through power lines from a plant to home and a very specific issue when dealing with hydrogen is that it is difficult to be stored (Roads2HyCom, 2009).

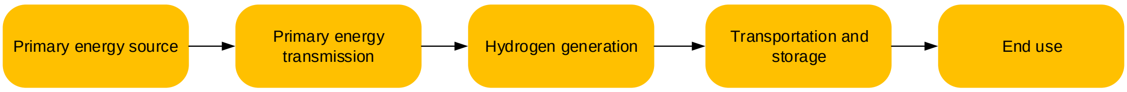


Figure 24: Typical hydrogen supply chain stages

Hydrogen is a chemical element which reacts with oxygen and produces both water and energy. It can be used as a fuel in combustion engines or to generate electricity in fuel cells. Its particularity relies on the fact that it is not a fuel that can be found and possibly extracted directly from nature but that has to be manufactured. The two most common production methods are:

- Hydrocarbon reforming – chemical conversion of hydrocarbons (natural gas, coal, oil) water and oxygen to into hydrogen and carbon dioxide.

- Electrolysis- splitting water into hydrogen and oxygen via electrical current

If considered in an SC way, the hydrogen SC comprises (Figure 24) the following stages:

- Source of energy
- Production technology
- Storage facilities
- Transportation mode
- Dispersing

Currently hydrogen applications and relative SCs, since this is a field under development are mostly market-driven, so operated and designed under techno-economic criteria. Nevertheless, there exist some works examining other dimension like social and environmental, which will be more explicitly mentioned in Chapters 4.4-4.5.

2.8 Background and emerging issues

In this section is discussed a background overview of the main issues and policy targets that have driven the introduction of the ESC conceptualisation for large scale applications. The different levels of decisions (as analysed in Chapter 2.5), the various types of energy planning problems (Chapter 2.7) as well as the expected outputs of the introduction of the specific evaluation framework are presented here with emphasis on ESCs.

2.8.1 The problem environment: The transition towards a low carbon economy, energy fuel mix diversification and security of energy supply

The European Union (EU) has set some major energy challenges to be met: climate change, increasing reliance on imported energy, fossil fuels' depletion and the need for equal access by both citizens and businesses to secure, safe and affordable energy. This presupposes the implementation of an ambitious energy policy - covering a wide range of energy sources from fossil fuels (oil, natural gas and coal), nuclear energy and renewables (solar, wind, biomass, geothermal, hydro and tidal) - on top of the energy efficiency improvement to lead to a low carbon energy economy: secure supply, competitive and sustainable production.

This policy was integrated into a strategic plan; that of energy and climate change, to which the EU was strongly committed. By setting high targets for energy efficiency, integration of renewables and low carbon economy, the program started in March 2007, and after months of negotiations between the member countries, it was adopted by the European Parliament in December 2008. This plan, was followed by an initial deadline for the adoption of the package in the European Parliament that was set in March 2009 (European Commission, 2011).

The plan included the so-called "20-20-20" target consisting of four major objectives that were:

- Reducing emissions of GHGs by 20% by 2020 in comparison to 1990 levels.
- Increasing energy efficiency to save 20% of EU energy consumption by 2020.
- The integration of RES to 20% of total EU energy consumption by 2020.
- The use of biofuels in the overall vehicle consumption by 10% by 2020.

The EU, heading towards an energy efficiency roadmap for 2050, also set binding targets for 2030, aspiring to reduce domestic GHG emissions by at least 40% below the 1990 level by 2030. This target was set to ensure that the EU is on track for achieving a more sustainable policy in 2050, setting very low emission ceilings (cutting emissions by at least 80%).

These set of policies and measures were to be adopted under a common framework by the EU member states respectively: each country has a significantly differentiated fuel mix, scale of economy, power and technological infrastructures and know-how, but it shares common targets for energy efficiency: supply of secure energy, energy bills' reduction and limitation of environmental impacts of energy production and consumption. However, if the majority of the EU is examined, one may notice that at the moment we are far away from balancing the production to consumption energy ratio (strong dependence on imports) and the investments in energy infrastructure projects have reached historical minima. Thus, an energy transition is required (Fouquet & Pearson, 2012, Foxon, 2011, Li et al., 2015, Miller et al., 2015) towards a less carbon intensive energy system (Hoggett et al., 2014a) under provisions of sustainability and social supported mechanisms (Zafirakis et al., 2013).

As Foxon (2011) states, "*transition to a sustainable low carbon economy will require radical changes to systems for providing energy and other services for individuals, communities and businesses*" involving changes both to energy practices and final use but also a strong initiation for the technological industry. A very important attribute to this end is the role of economy and industrial innovation to fuel mix diversification accounting simultaneously environmental and social implications on top techno-economic ones.

On the other hand, a major driving force to this step-wise transition is the security of energy supply. As IEA states (2014), energy security is "*the uninterrupted availability of energy sources at an affordable price*". The main particularity of energy security is that it has both long term and short term dimensions: under short term energy security the focus of attention is paid on meeting the demand and under long-term, making the appropriate investments to support secure energy under the provisions of sustainable development for future generations.

2.8.2 Specific issues raised from the electricity generation sector

Considering the electricity generation sector, being the study focus of the present work, energy market integration, cross-border trade and the implementation of energy and climate targets for 2020 have prompted international awareness. Electricity generation in the EU accounts for more than 30% of anthropogenic emissions (Gibon & Hertwich, 2014), providing a significant margin of improvement, investigation, and if possible optimisation of the present situation. According to the latest available energy data (European Commission, 2014a), the current EU-28 electricity generation mix is almost equally based on solid-fossil fuels and nuclear power (27%) with renewables (with major contribution of hydro power) following – 24%. The natural gas share has continuously decreased over the last three years– from 24% in 2010, to 22% in 2011 and 19% in 2012. The oil share remained stable at around 2%, with Cyprus and Malta alone being the two Member States that rely almost entirely on oil for electricity generation. In terms of imported energy, EU is the world's largest energy importer EU, with import dependency on solid fuels, crude oil, petroleum products and gas in 2012 reaching 42.2%, 86.4% and 65.8% respectively (European Commission, 2014b).

At the moment the European electricity sector has prioritised GHG emissions' reduction, price policy and price control (meaning that there will be transparency in price creation, formulated by the origin of the electricity generated), dependence reduction from primary energy imports outside the EU27 and efficiency improvement to reduce cost of generated electricity. With this agenda and with the help of energy storage solutions (such as batteries or pumped hydro storage systems) for balancing the fluctuations between demand and supply at different time scales, greater penetration of RES as well as fuel mix diversification is expected.

Thus, the great challenge today is to reform and optimise the current energy systems, and possibly introduce new systems for meeting both GHG emissions' reduction and secure energy supply. To this side, the SCM concept supports the identification of different energy and fuel SC topologies and stresses their integrated evaluation: policies and measures, actors and policy makers, different type of information are all identified across the SCs, contributing to optimally predict, control and minimise the possible risks and uncertainties. In addition, the SC concept has significantly supported strategic decision-making, by incorporating and engaging agents and markets that together form the internal and external environment of the systems considered. By identifying the connections between them, diversification strategies and energy security issues can be assessed more effectively.

That is why a series of indicators (Weinzettel et al., 2012), SC topologies and scenarios (Messagie et al., 2014) along with qualitative and quantitative models (Palander, 2011), have been developed for the electricity sector, altogether comprising a useful toolbox for effective decision making that accounts for both environmental and social dimensions, on top of techno-economic ones. Such indices and parameters concerning electricity SCs in particular will be introduced in Chapter 4.

2.8.3 Assessment of multiple dimensions in energy supply design and operation

Energy systems, may be characterised as the "*connection, a physical way, of the facilities of energy generation/conversion, to a certain form (e.g. electricity, heat), the storage facilities, the transmission facilities and the distribution facilities that operate as a complete system*" (Theodosiou et al., 2015). The SCs are of a dynamic nature, since each policy decision is characterised by diverse actors, technological options, time scales and spatial dimensions, on top of the goal of fully meeting society energy needs either for heat, power or fuels.

All these decisions are case-specific and subject to location-specific attributes: Institutional implications like rules and regulations being applicable in each country (or specific area), social implications and pressures, i.e. acceptance of new infrastructure projects, either in favour or against of the operation of plants. To this end, energy policy institutions nowadays come to adopt more expansive conceptual frameworks that integrate social considerations more effectively into energy analysis and decision-making (Miller et al., 2015).

Moreover, it is the concept of “energy transition” that considers the option of transforming the energy mix of a country, passing from a non-renewable mix to a renewable mix, in order to achieve a sustainable energy system in terms of environmental protection, industrial and technological development, reduction of energy dependence and regional cooperation (Ivanov & Sokolov, 2010).

In this context, SCM supports the integration of all existing dimensions in the energy systems' design and operation; environmental and social ones that may be involved into processes of energy design, planning, on top of the techno-economic ones. This requires a good knowledge of the system under examination, acknowledging which stakeholders are involved and in what way they do so (consumers, producers, private and public investors, local residents, the government), which are the technological pathways (what are the technological options, what are the limitations of technology and their environmental impacts, which technologies are the most suitable for which case, what is the current know how and cost), what is the status of the environment and the local limitations, emissions and air quality ceilings, what is the attitude of the local society for the under examination system and which are the benefits that may result in macro and micro economic terms.

In more detail, the conceptualisation of the SCs in energy systems planning and operation significantly supports the identification of the types of decisions that are involved in the SCs and enables decision making under a wide nexus of parameters, implications and conflicting interests amongst the different stakeholders interrelated in the SC network. In Chapter 2.9 following, a short discussion about the types of decisions supported by the energy and fuels SC introduction is given.

2.9 Types of decision involved in SCs

The decision making environment under which the SC management and optimisation has been introduced involves cross sectional factors affecting the decisions to be implemented in the integrated network: improved efficiency under new technological options and reduced cost goals, techno-economic considerations under new sustainability mandates, life-cycle considerations in product design and delivery, improved sustainability performance of the integrated SC in terms of minimising the environmental and social implications.

Considering the distinctive stages of the SCs, under the design of new and existing SCs the critical decisions involved include:

- Raw material, feedstock production - type of raw materials to facility plants
- Distribution / logistics - optimisation of the existing network infrastructure and or in the case of design of new plants, optimum facility siting
- Manufacturing / production process (inventory-storage)/ selection of the optimum technological option accounting simultaneously economic, environmental and social negative impacts' minimisation
- The demand side (retailers, customers)- which products should be delivered from each facility to the appropriate market based customers.

These types of decisions involve parameters that may have location-specific parameters and production costs (Shah, 2005):

- Time frames and design horizon (operation, planning, strategic)
- Network and manufacturing complexity issues (number of products and raw materials being delivered to end customers through different and multiple pathways).

Models that have been applied in the Process industry may be classified primarily as dynamic or steady state and as deterministic or dealing with uncertainties. However the problems assessed by the supply chain as early analysed by Shah, (Shah, 2005) may fall under three distinctive categories: (i) SC infrastructure (network) design; (ii) SC analysis and policy formulation; (iii) SC planning and scheduling. Other and more recent type of problems involve the assessment and quantification of non-measureable factors and parameters that have serious implications in the SCs sustainability performance. Modelling approaches in detail will be examined in Chapter 3.5.

2.9.1 Location distribution problems

A very particular aspect of energy supply design, planning and operation is the location of the plants and the energy distribution network. SC infrastructure and network design seeks to identify the optimal network configuration and how all the components of the SC (resources, actors and facilities/plants) must be allocated and coordinated under the optimisation goals with the predominant one being the cost minimisation. These types of problems may be characterised as rather practical ones as they have been trying to assess both quantitative (number of production being delivered to end customers, number of production facilities and warehouses) and qualitative issues, like identification of the optimal vehicle routing, siting and location identification of new plants, or in the case of an existing system, capacity expansion consideration.

To that end, early enough Bookbinder & Reece (1988), as an indicative example, introduced MILP for optimising a distribution planning system for multiple commodities under the criterion of cost minimisation. Geoffrion & Graves (1974) considered the problem of optimal location of distribution facilities between plants and customers. In this context, MILP was applied to model a real food, large scale SC problem, under the multi-commodity flow problem assessed for a single period. The problem involved 17 commodity classes, 45 possible distribution centres, 14 plants and 121 customer zones. Under the same field, in the food industry for example, Brown et al., (1987) modelled a facility selection, equipment location and utilisation, as well as manufacturing and distribution of multiple commodities under an MILP model formulation.

2.9.2 Examination of energy systems

Energy planning today is complicated as many parameters, decisions and stakeholders are involved in each energy supply option. Depending on the level of decision (tactical, strategic and operational planning) selection of an energy supply option may vary significantly if all dimensions of sustainable development are considered i.e. economic, environmental and social. At a national level, this may result in a completely different fuel mix and energy sources' utilisation and thus support a differentiated national policy plan. On the other hand, at the operational – micro-scale level, it may reveal the environmental and socially just utilisation of existing resources.

The country-level approach emphasises two axes: at the operational / planning level primarily evaluating the existing situation (utilised energy fuel mix for power generation not only in techno-economic terms but also accounting simultaneously social and environmental implications) and secondly at the strategic level supporting decision making on new energy infrastructure projects, taking into consideration sustainability dimensions as well as the positive match of them (in terms of employment creation, economic reinforcement and minimisation of exchange losses due to the elimination of imported- fossil based resources) for the society in its all.

Isolated consumers on the other hand face the energy threat in a particular way: apart from the security of supply issues and the regulatory barriers that may exist in particular areas, the problems are most evident as the limited generation capacity in the case of failure may has a greater impact on the overall systems. On top of that, due to the size of the power supply options, economies of scales are difficult to benefit. However, opportunities emerging from RES penetration along with the integration of energy storage technologies, can lead to more sustainable energy systems which will have a beneficial impact to the respective population served. So the specific challenges arising are the reduction of the reliance of remote communities on fossil fuels, by the introduction of more renewable generation assisted by hybrid energy solutions.

In the present research work a three level analysis for two different types of consumers will be carried out, emphasising on the respective types of decisions accounting not only for techno-economic considerations but also macro-economic benefits arising from social and environmental issues: A small, non-interconnected consumer in a typical Greek island in the Cyclades (simulated as an entire island- single island cases- APPENDIX C), A larger group of consumers modelled under the exemplar paradigm of a complex of interconnected islands, with multiple resources, limited RES penetration and intense load variations (set of island cases)- Chapter 6. However prior to the case studies, a short review on optimisation methods and tools, with special emphasis on the support of energy decision making will be made in the following Chapter (Chapter 3).

CHAPTER 3: OPTIMISATION METHODS AND TOOLS

In this chapter, specific optimisation methods, tools and techniques are introduced with emphasis given on their utilisation for the evaluation of energy and fuel SCs. On top of that, the types of problems being assessed and the types of tools that are available for the different SCs are briefly explained along with their applications.

3.1 About optimisation

Optimisation methods and tools have been widely applied to energy and environmental problems seeking to eliminate the degree of uncertainly related to energy decision making (Kondili, 2005, Suganthi & Samuel, 2012). In addition, originating also from the Process industry, a wide range of optimisation models have been developed in order to address practical problems within energy optimisation, as material scheduling, resource utilisation, equipment design and operation (Alexander et al., 2000, Liu & Papageorgiou 2013, Papageorgiou, 2009). In the more recent field of energy planning, models and tools have been extensively used for supporting optimum allocation of energy resources, technologies and relevant services under single or multiple objectives (Flores et al., 2015, Zeng et al., 2011).

Energy systems, in complete accordance with process systems, integrate a set of processes, to which we will later refer as tasks i.e. energy and fuel exploration and exploitation, conversion and processing, production and consumption, import and export. So, the examination of the existing models should focus on identifying the energy and fuel SC under consideration, the various constraints and parameters of the system as well as the type of approach used for solving the problem. In addition to that, the development of an effective and systematic framework of approach can successfully address complexities, and uncertainties involved in the under consideration systems. At the same time, it can also provide decision makers with the adaptability and flexibility of switching between different optimisation targets or moderating the problem under new mandates and parameters that may occur.

Generally, optimisation problems can be classified into various categories (Rao, 2009, Ravindran et al., 2006) based on:

- the existence of constraints (constrained or unconstrained problem),
- the nature of the design variables (parameter or static optimisation problems (when the problem is to find values to a set of design parameters that make some prescribed

function of these parameters minimum subject to certain constraints) and trajectory or dynamic optimisation problems (design variable is a function of one or more parameters)

- the physical structure of the problem, as optimal control and non-optimal control problems[1]
- the nature of expressions for the objective function and the constraints. According to this classification, optimisation problems can be classified as linear, nonlinear, geometric, and quadratic programming problems.
- the number of objective functions to be optimised (single and multiobjective programming problems). According to this classification, the analysis of the main mathematical programming problems will be made in Sections 3.1.1 and 3.1.2.

3.1.1 Single-objective optimisation

When the mathematical relations describing the problem (objective functions and constraints) are linear in the decision variables then the problem is characterised as a linear programming problem (Linear Programming, LP), while in the case that non-linearities exist, it is classified as a problem of Nonlinear Programming (non- Linear Programming, NLP). Linear Programming problems are the vast majority of programming problems, mainly due to their specific characteristics and the easiness of model formulation and solving. In addition, a very important distinction, is also whether the NLP problem is convex or non-convex, since the latter may give rise to multiple local optima.

Linear programming can be characterised as a problem of maximisation or minimisation of a linear objective function, subject to linear constraints (of equalities and inequalities). In its standard form, it is represented by Equation 1:

$$\begin{cases} min\ c^T x \\ s.t.\ Ax=b \\ x \geq 0 \end{cases} \tag{1}$$

where $c \in R^n, b \in P^m$ and A is an $m \times n$ matrix of rank m.

[1] *An optimal control (OC) problem is a mathematical programming problem involves a set of stages, and each stage evolves from the preceding stage in a prescribed manner. It is usually described by two types of variables: the control (design) and the state variables (Rao, 2009).*

The feasible domain $P=\{x \in \mathbb{R}^n : Ax=b,\ x \geq 0\}$ is a polytope. We assume that (1) has a finite optimal solution. Let B be a submatrix of A formed by m linearly independent columns. We may assume that $A=[B,N]$ i.e. the first columns of A are linearly independent. Then the linear system $Bx_B = b$ has a unique solution. If $x=(x_B,0)$ then $Ax=b$ and $x=(x_B,0)$ is called a basic solution. The components of x associated with the columns of B are called basic variables. If one of the basic variables in a basic solution is zero, that solution is called degenerate basic solution. A basic solution that is feasible *i.e.* $x \geq 0$ is called basic feasible solution.

Another classification is according to the type of the decision variables: if they are continuous or integer. Problems with integer variables suggest a more difficult resolution process mainly due to the fact that a subset of variables is required to take on certain discrete values. On the other hand, the possibility of using integer variables enables a more realistic modelling of reality and also significantly expands the scope of Mathematical Programming and problems that are of combinatorial nature. A model that has only integer variables is characterised as Integer Programming Model (Integer Programming, IP) and if it has continuous and integer variables is characterised as Mixed Integer Programming Model (Mixed Integer Programming, MIP). When a model combines also aspects of non-linearities, it is characterised as an MINLP (Mixed Integer Non-Linear Programming).

The integer programming, is a type of linear programming model formulation that variables are restricted to be integers. Only in the case that some of the variables are integers we have MIP. Such a problem formulation can be stated as follows (Floudas & Pardalos, 2009)- Equation 2:

$$\begin{cases} \min\ cx \\ s.t.\ \ Ax \geq b \\ \qquad x \geq 0 \\ \qquad x_j \ \ integer \\ \qquad j \in N_1 \subseteq N, \end{cases} \tag{2}$$

where A is an $m \times n$ matrix, c and b are given vectors of conformable dimensions, $N := \{1,...,n\}$ and x is a variable n-vector. The “pure” integer programming is the case of MIP when $N_1 = N$. If in addition all entries, A,b,c are integers, then the slack or surplus can be also be restricted to integers.

Other types of model formulations, forming subsets of LP, are the Linear Complementarity Problems (LCP), in which certain pairs of inequality constraints must be complementary (Fourer et al., 2003), (Billups & Murty, 2000). In its standard form, an LCP problem is stated in terms of mapping (Floudas & Pardalos, 2009)- Equation 3:

$f : R^n \to R^n$ where $f(x) = q + Mx$.

Given f, one seeks a vector $x \in R^n$ such that for

$$i = 1,...,n,\ \ x_i \geq 0,\ \ f_i(x) \geq 0, \text{and}\ \ x_i f_i(x) = 0 \tag{3}$$

Because the affine mapping f is specified by the vector $q \in R^n$ and the matrix $M \in R^{n\times n}$ the problem is ordinarily denoted LCP (q,M) or sometimes just (q,M). A system of the form (3) in which f is not affine is called nonlinear complementarity problem and is denoted NCP(f). The notation CP(f) is meant to cover both cases. If $\bar{x}$ is a solution to (3) satisfying the additional non-degeneracy condition $\bar{x}_i + f_i(\bar{x}) > 0,\ i = 1,...,n,$ the indices i for which $\bar{x}_i > 0$, or $f_i(\bar{x}) > 0$, form complemental subsets of $\{i = 1,...,n\}$. This is believed to be origin of the term complementary slackness as used in linear and nonlinear programming (Floudas & Pardalos, 2009). An overview of the optimisation classes and relvelant problems by the review work of Biegler & Grossmann (2004) is illustrated in Figure 25.

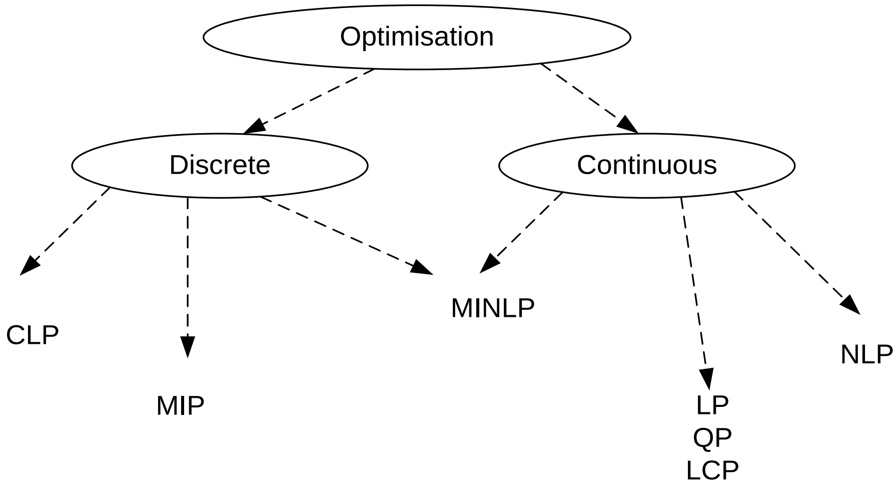


Figure 25: The classes of optimisation problems (Biegler & Grossmann, 2004)

A more "modern" programming category is the Stochastic Programming. The Stochastic Programming (Stochastic Programming, SP) or unclear Programming (Fuzzy Programming, FP) is a framework for modelling optimisation problems that involve uncertainty (Fouskakis & Draper, 2002, Kacprzyk & Orlovski, 1987). While the deterministic optimisation problems are formulated with known parameters, the problems of the real world almost always include some unknown parameters. The goal here is to find a policy that is feasible for all (or almost all) the possible cases of data and maximises the expectation of a function of the decisions and random variables.

3.1.2 Multi-Objective Optimisation

Seeking to address a wide range of multiple and conflicting decisions, Multi-objective Programming (Multi objective Programming) has been introduced (Miettinen & Słowi, 2008). Multi-objective Programming or multi-objective optimisation (MOO) is an area with multiple decision making criteria, dealing with mathematical optimisation problems that allows more than one objective function(s) to be optimised simultaneously. Minimising cost, while maximising comfort by buying a car and maximizing performance while minimising fuel consumption and emissions of a vehicle are examples of the many objective optimisation problems involving two and three goals respectively. However, in real problems the conflicting goals and decisions are much broader and more interrelated. In this type of problems, usually there is no single optimal solution but a set of alternatives with different trade-offs, called Pareto optimal solutions. Mathematically, the multiobjective optimisation problem can be expressed as-Eq.4:

$$(MOO)\begin{cases} max\, f(x), \\ s.t. \;\; x \in X, \end{cases} \tag{4}$$

where $X \subseteq R^n$ is the set of alternatives and $f = \left(f_1,..., f_p\right): R^n \rightarrow R^p, p \geq 2,$ is a vector-valued function. X can be any set, continuous or discrete, xpressed through constraints, and the objective function f can be of any form. In MOO the concept of optimality has a different meaning, as each objective function would possibly result a diverse optimal solution. Therefore *"solving the (MOO) problem is about studying the inherent trade-offs among conflicting objectives. Efficient solutions are the ones that possess the relevant trade-off information"* (Floudas & Pardalos, 2009). An $x^o \in R^n$ is called an efficient solution for MOOP if $x^o \in X$ and there exists no $x \in X$ such that $f\left(x\right) \geq f\left(x^o\right)$ with strict inequality holding for at least one component. The set of all efficient solutions are usually denoted by X_E. So, the most-preferred solution should belong to X_E, as solutions that are not efficient, the dominated ones, can be improved upon in at least one objective without worsening the others. The difficulty of identifying the most-preferred without the involvement of the decision maker in the solution procedure has resulted in very different solution approaches to the (MOO) problem.

3.2 Optimisation methods

In the following section the most widely applied methods for the solution of LP models are presented in respect to their complexity as well as delimitations.

3.2.1 Graphical Method

If an LP problem involves only two variables, then it can be represented graphically and the optimal solution of the objective function can be located in one of the end points of polygon. Some basic points in the case of a maximisation problem include the following steps and illustrated in Figure 26:

- Expression of the constants as equations (changing the ≤ or ≥ with =)
- Plotting the constraints of the functions
- Identification of the feasible region
- Determination of the direction of improvement for the objective function
- Identification of the optimal solution along the feasible region's boundary or inside (all of the points that correspond to feasible decisions)
- Optimal solution may be found at the end points / corners of the solution space (polygon)

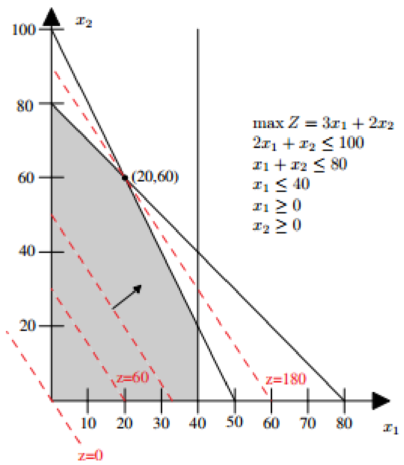


Figure 26: LP standard method (Chinneck, 2001)

3.2.2 Simplex method

One of the most popular methods used for the solution of Linear Programming Problems is the Simplex method. The Simplex method, was invented by George Dantzig in 1947 and since then, along with its refinements, is used as a basic workhorse for solving linear programs, even today. While there have been many refinements to the method, especially to take advantage of computer implementations, the essential elements are the same as they were when the method was invented.

As analysed above, in any LP problem having a solution, an optimal solution appearing corresponds to a corner of a "sketched" polygon as in Figure 27, although there may be multiple or alternative optimal solutions. Considering a corner as the starting point, the solution can move to the neighbouring corner that best improves it. This repetitive action is conducted, making the greatest possible improvement each time. The action is terminated when the most attractive corner corresponding to the optimal solution has been found. The steps followed are:

Step 1-Initialisation: is about finding an initial Feasible Basic Solution (FBS) to the problem (this solution will be called the current FBS).

Step 2 - Optimality test: is about identifying if the current basic FBS is optimal. If no, we must proceed to the Iteration. If yes, we can stop.

Step 3 Iteration: is about performing an iteration to find an adjacent FBS to the current one that has a larger (not smaller) Z - value (for a max problem) and a smaller Z value (for a min problem). We must return to Step 2 using the new FBS as the current FBS.

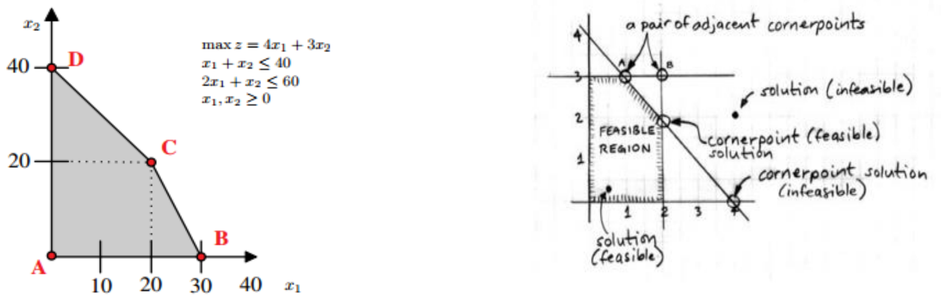


Figure 27: The representation and the vocabulary of the simplex method after Chinneck (2001)

3.2.3 Branch-and-Bound method

Branch and Bound (B&B) is another widely used method for solving integer programming optimisation problems. B&B, has numerous choices and alternatives, being adaptive to each specific problem type (Chinneck, 2001). It considers the solution space in a tree based structure (Figure 28), which each node of the tree corresponding to a sub problem of the original problem and includes the initialisation (start-up) phase from the corresponding node and a set of interactions, traversing the tree and exploring the most promising subtrees till the end (Clausen, 1999).

Each iteration encompasses:

(a) Branching - deciding which node to branch among the "active" nodes in the tree and which variable from the fractional ones is to be branched (generally we choose an integer variable that it is basic and fractional in the LP solution and split the problem into two about this fractional value)

(b) Bounding – deciding in each of the developed nodes, which nodes to be fathomed "pruning the branches"

(c) Fathoming "pruning the tree"- deciding from the active nodes which ones be discarded. This step also includes a termination criterion. In more detail, the process steps are as follows:

Initialisation

In the tree-based structure, the initial node corresponds to solving the LP relaxation from the given ILP by "ignoring" integer constraints of the variables. This node is called "active" and is set as the starting point for the upcoming interaction. Starting from the root node, some of the variables are systematically fixed (to 0 and 1) to generate intermediate nodes of the branch and bound tree.

Typical Iteration for maximisation problem

a) Branching. One "active" node is selected (we branch on an integer variable, where on each branch, the integer variable is restricted to take certain values).

(b) Bounding. At each new node, the LP corresponding problem is determined and solved. The non-integer values are rounded down to nearest integer ones. This is the bound of the sub problem at the node.

(c) Fathoming. For each new node (sub problem) three solution options are equally tested: (1) Integer solution. If one of the new nodes has integer solution, its bound is compared to the bounds of other such nodes. If it does not have the best value - it is fathomed. If it has the best value, it is fathomed and it is our current best solution Z* (incumbent). (2) Bound value. If any of the new nodes has a bound smaller than currently the best bound Z* - fathom the node. (3) Infeasibility. If LP at any of the new nodes has no solution (not feasible) – fathom the node.

Termination: The interaction is stopped when there are no more sub problems (no branching). The node with the best value provides the solution.

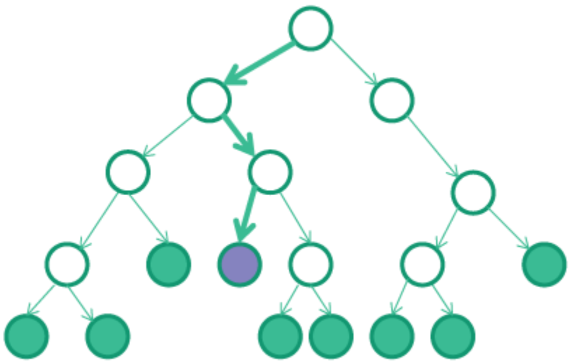


Figure 28: Typical illustration of the Branch and Bound method

3.3 Optimisation tools for LP problems

In this section, some of the main optimisation tools are presented.

3.3.1 EXCEL (Solver)

Excel is an application computer table developed by Microsoft and supported by Microsoft Windows and Mac OS. It features calculation, graphing tools, pivot tables and a macro programming language Visual Basic for applications. It also features a tool called Solver using techniques from operational research to find the best solutions for all kinds of decision problems.

The Solver is part of a series of commands that are sometimes called what-if analysis tools. With Solver, one can find an optimal value for a formula in a cell - called target cell - on a worksheet. The Solver works with a group of cells that are related, directly or indirectly, to the type of target cell (Figure 29). Restrictions can be applied to limit the prices that the model will use and constraints can apply that refer to other cells called cells-constraints. Thus, using the Solver has 3 main components that should be familiar to the user:

1. Cell Target (Target Cell). This is the cell that represents the target or object of the problem. It includes the objective function (i.e. Equation 1) that the program sets for optimisation and should be expressed as model-formula of the decision variables.
2. Changing-Cells (Changing Cells). They are the cells that can be modified to get the desired result. Generally, it is a set of cells that contain the values that will be produced by the function of the decision variables (cell target) when optimising. In these cells the resulting values of optimisation for the for example to x_1, x_2 decision variables, will be returned.
3. Cells-Restrictions (Constraints Cells). These are restrictions or limits for which the Solver must screen the set of feasible solutions (for example in the linear optimisation problem analysed above problem constraints include the following equations: $x_1 + x_2 \geq 14$ and $x_2 \geq 5$ and $x_1 \geq 0$). These constraints must be satisfied simultaneously.

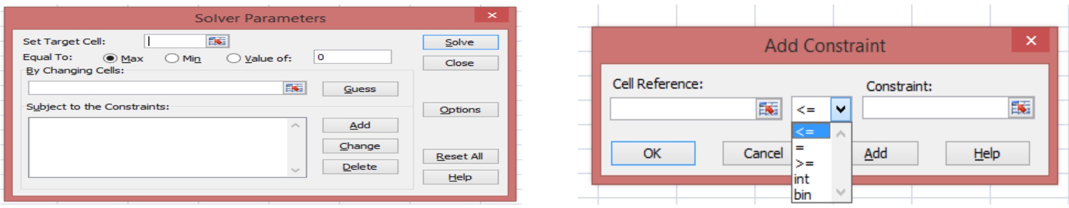


Figure 29: The excel solver interacting environment

The standard Microsoft Excel Solver has a limit of 200 decision variables, for both linear and nonlinear problems and was therefore insufficient for the scope of this thesis.

3.3.2 OpenSolver (Excel add-in)

OpenSolver is an Excel VBA add-in that extends Excel's built-in Solver with more powerful solvers. It is developed and maintained by Andrew Mason and students at the Engineering Science department, University of Auckland, New Zealand and provides a wide range of solvers for use in Excel, including the Open Source COIN-OR CBC optimisation engine that can quickly solve large Linear and Integer problems. It is an open-source software, with no artificial limits, compatible with the existing solver models (Mason, 2011). OpenSolver, as illustrated in Figure 30, has been developed for Excel 2003, Excel 2007, Excel 2010, and Excel 2013 (including the 64bit versions) running on Windows, and supports Excel for Mac 2011 on Mac OS X.

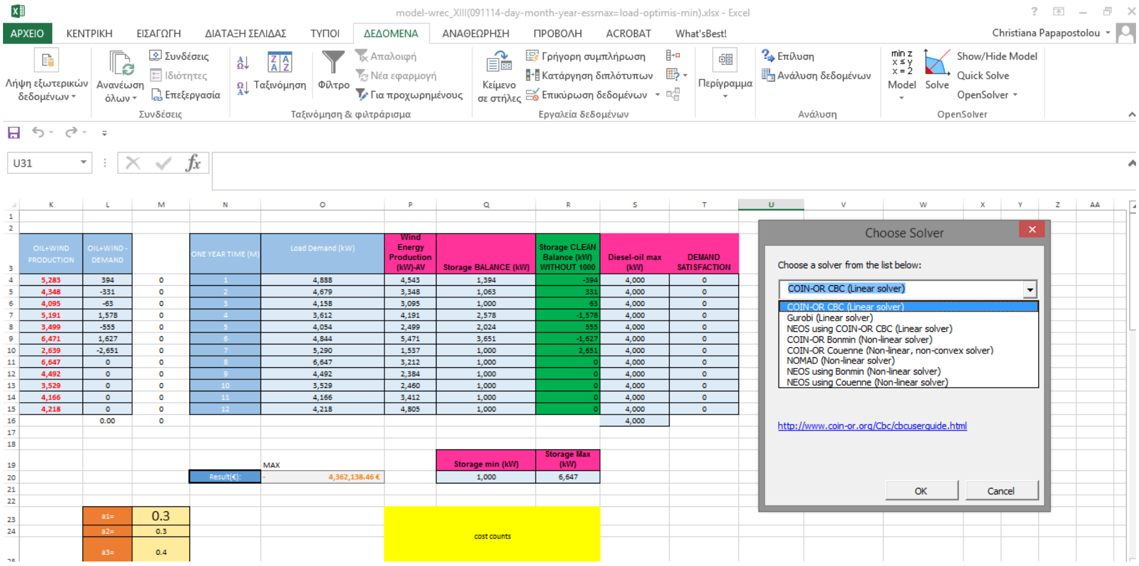


Figure 30: The open-solver modelling platform

3.3.3 General Algebraic Modelling System - GAMS

The General Algebraic Modelling System (General Algebraic Modelling System, GAMS) is designed for the analysis of almost all the well-known optimisation problems (linear, nonlinear mixed integer, stochastic etc). The system is particularly useful for large and complex problems, while allowing the user to focus on the problem of the model by making a simple organisation. The user can change the formulation quickly and easily convert a linear problem in a nonlinear one without great difficulty. The language used by the GAMS is similar to typical programming languages, thus making it easy to handle for anyone with basic programming background.

Using GAMS, data are entered only once with the known form of lists and tables. All restrictions of the problem are entered into statements and GAMS automatically generates the constraint for each equation and lets the user make exceptions in cases where generality is not sought. The design in GAMS (Figure 31) has incorporated concepts from the database theory and mathematical programming and tries to merge these ideas to meet the needs of planning models. The relevant database theory provides a structured framework for general organisational abilities, transforms the elements of the model and combines with the mathematical programming, offering a variety of methods that help in solving difficult problems.

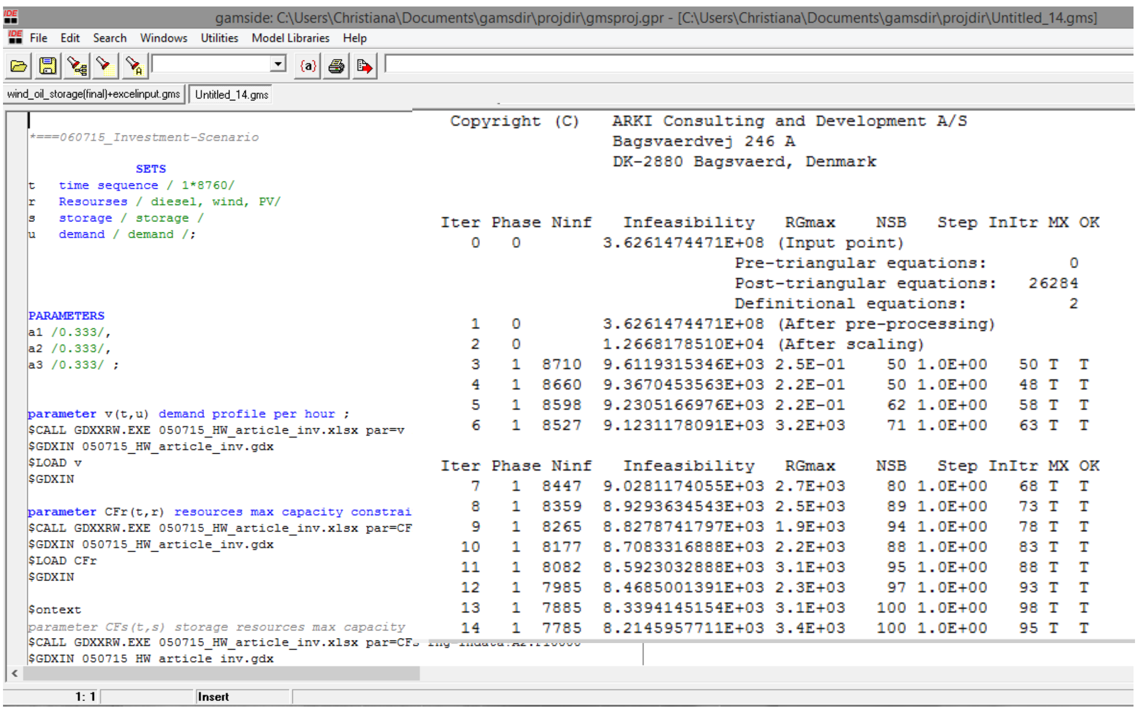


Figure 31: The GAMS modelling plaform data entry and compile window (www.gams.com)

3.4 Optimisation methods for multi-objective problems

3.4.1 The scalarisation technique/ weighted sum method

A common method for solving multi-objective problems is by combining multiple objectives into a single-objective problem, by weighing them relative to some measure of their importance and add them to form a scalar function. This approach is called weighted sum or scalarisation method. More precisely the weighted sum method minimises (or maximises) a set of positively weighted convex sum of objectives – Eq.5:

$$\begin{aligned}
&min\sum_{i=1}^{n}\gamma_i\times f_i\left(x\right)\\
&\sum_{i=1}^{n}\gamma_i=1\\
&\gamma_i>0,\ i=1,...,n\\
&x\in S,
\end{aligned}\tag{5}$$

where x is the vector of decision variables, $f_i=\left(f_1,...,f_n\right)$ are the n objective functions, S is the feasible region, and the weighted sum is a convex combination of objectives. Each objective represents one optimal solution in the Pareto front. If the "γ" weight vector is strictly greater than zero, then the minimiser is a strict Pareto optimum, while in the case that there is at least one $\gamma_i=0$ then it is a weak Pareto optimum.

In this method it has to be underlined that "*it is up to the decision maker to choose appropriate weights, noting that weighting coefficients do not necessarily correspond directly to the relative importance of the objective functions*". In addition, as the decision maker "*cannot be aware of which weights are the most appropriate to retrieve a satisfactorily solution, he/she does not know in general how to change weights to consistently change the solution*". Also the decision maker needs to choose a priori different weighting combinations to reporduce a representative part of the Pareto front, because the repetitive interaction with different weight values can be time consuming.

The well-known drawbacks of the weighted sum method relate with the fact that the optimal solution distribution is not uniform, and that optimal solutions in non-convex regions are not detected (Figures 32a, b).

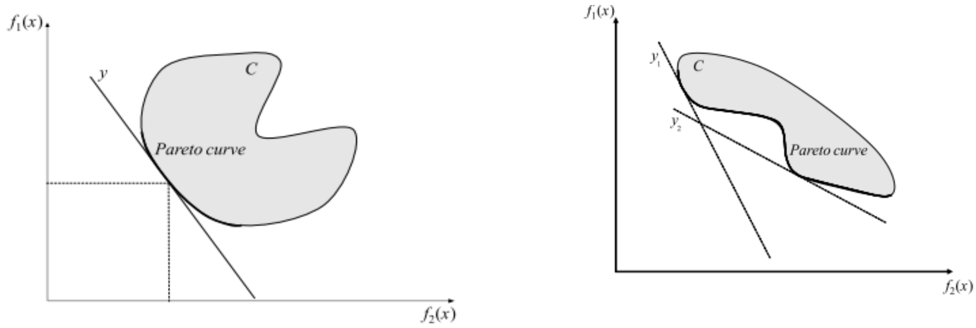


Figure 32a,b: Geometrical representation of the weighted–sum approach in the case of convex (a) and non-convex (b) Pareto curve

Seeking to provide solutions to the above, the Adaptive Weighted Sum (AWS) method was developed recently by Kim & de Weck, (Kim & de Weck, 2004). By imposing additional inequality constraints in the typical weighted sum method, the optimisation is performed only in a newly-defined feasible region where more exploration is needed. The adaptive weighted sum method successfully solves multi-objective optimisation problems: the AWS method produces well-distributed solutions, finds Pareto optimal solutions in non-convex regions, and neglects non-Pareto optimal solutions.

Considering the specific multi-objective problem, the weighted sum method was selected by applying equal weights ($a_1 = a_2 = a_3 = 0.333$) to the n=3 number of objective functions, seeking to evaluate the techno-economic, environmental and social implications of the ESCs examined. However, the optimisation criterion with the weighted factors in each special dimension, economic, environmental and social, provides the flexibility to the user to adjust his decision considering the special characteristics and needs of each energy planning problem e.g. special emphasis may be given to the environmental criterion if the area under examination implies an environmental degraded profile.

3.4.2 ε-constraint method

Another technique for solving multi-objective optimisation problems is the ε-constraint method initially proposed in 1983 by Chankong and Haimes (Miettinen & Słowi, 2008). Under this problem formulation, the decision maker chooses one objective out of *n* to be minimised, whilst the remaining ones are constrained to be less than or equal to given target values - Equation 6.

$$\begin{aligned} & min\, f_i(x), \\ & f_i(x) \le \varepsilon_i, \\ & i=1,...,n, \\ & x \in S \end{aligned} \tag{6}$$

where x is the vector of decision variables, $f_i = (f_1,..., f_n)$, n the number of objective functions and S is the feasible region. If an objective n and a vector ε $\varepsilon = (\varepsilon_1,...,\varepsilon_{j-1},\varepsilon_j,\varepsilon_{j+1},...,\varepsilon_n) \in R^{n-1}$ exist, such as x^* is an optimal solution in the following problem - Equation 7:

$$\begin{aligned} & min\, f_i(x), \\ & f_i(x) \le \varepsilon_i \forall i,\ i=1,...,n,\ \not\subset \{j\} \\ & x \in S \end{aligned} \tag{7}$$

then x^* is a weak pareto optimum. Whilst x^* is a strict pareto optimum if and only if for each objective $j(j=1,...,n)$ *there exists* a vector ε $\varepsilon = (\varepsilon_1,...,\varepsilon_{j-1},\varepsilon_j,\varepsilon_{j+1},...,\varepsilon_n) \in R^{n-1}$, such that $f(x^*)$ is the unique objective vector corresponding to the optimal solution of the problem (Miettinen & Słowi, 2008). One of the advantages of the ε-constraint method is that it is able to achieve efficient points in a non-convex Pareto curve. Nevertheless, among the disadvantages is that the method is not particularly efficient when the number of the objective functions is greater than two.

3.5 Mathematical programming applications in the field of energy and fuel Supply Chains

In general, one could point out that under the wider field of energy planning models, pollution prevention and control models, GHGs' mitigation models as well as, more recently, models converging on the optimisation of renewable energy systems (biomass, wind, geothermal energy etc) can be found. However, the focus of attention of the research community was triggered especially by trying to link both conventional and renewable energy sources. To that end, economic viability and societal efficiency, together with techno-economic considerations and market based instruments and structures (examining both the market operation i.e. monopolistic as well as the market needs based on the different types and levels of consumers) have been incorporated in energy modelling and relative applications (Borg, 1981, Landsberg, 1976), Rehman et al., 1998, Stern, 1977). However, over the years, the need for supporting decision making in the field of energy management and planning, resource allocation, either on the selection over multiple technological options, or at the local or national scale (Zeng et al., 2011) has been the study objective of several researchers. Their goals were to look into the identification of reduced dependency on fossil fuels, larger integration of RES both in large systems but also in stand-alone applications (Zhou et al., 2010), (Kaldellis, et al., 2009b, Zhou et al., 2010) always in terms of sustainable development (Lund, 2007) and assessment of indicators and performance indices (Evans et al., 2009).

In the present work, special focus is given in the investigation and relative review of energy planning and supply and demand models under the SCM concept, with particular emphasis on the energy and fuel SCs. Thus, following that, a short review of the optimisation models, approaches and types of problems being faced will be given in the next section with the starting point being biomass and biofuels, hydrogen, natural gas, petroleum-based, and finally wind and solar energy applications.

3.5.1 Biomass and biofuels

Being triggered by the fact that fossils fuels need to be replaced, the quest over alternative energy sources has lead from early on to biomass SC evaluation. From wood chips to pellets, energy crops, and waste, biomass has been encouraged as an energy production resource in all relative sectors, as it may present a substitute fuel for heat, power and transportation applications. That is the reason that the technical viability, on top of economic issues, has been studied extensively by the research community, looking for the most viable solution, by introducing modelling, simulation and decision making approaches. Beyond single stream and single optimisation approaches in the field of biomass, holistic works and review papers have been introduced seeking to enlighten the interrelation of this field of approach.

More precisely with emphasis given on biomass optimisation and production as well as on the identification of the available configuration and energy supply streams, Rentizelas (2011), and more lately Rentizelas & Georgakellos, (2014) introduced a handbook of biomass supply chains. A detailed analysis is provided on the available types of biomass and waste streams in respect to their origin and availability, to the structure of the biomass SC itself, as well as to the types of stakeholders and the issues they are being engaged. Special emphasis is given in economic dimensions with respect to the future trends' identification, by reviewing associated works in the field.

In the field of techno-economic evaluation, Papapostolou et al., (2011b) introduced a modelling approach for optimal exploitation of biomass to heat, power and biofuels. The optimisation problem is modelled as MILP reflecting the techno-economic considerations of the system approach, at the level of strategic decision. Model results reflect the optimum utilisation of resources to heat, power and biofuels' production.

Akgul et al., (2012b), assessed the problem for the optimal design of a hybrid ethanol supply chain in the level of strategic design. The mathematical model is formulated as a steady-state MILP by minimising the total cost (production, investment and outsourcing) of the SC accounting simultaneously sustainability constraints i.e. food competition and sustainable land utilisation.

Yilmaz-Balaman & Selim, (2014) introduced a fuzzy multi-objective MILP model in order to optimise a biomass-to-energy SC for regions with high availability of resources i.e. animal wastes and energy crops. Decisions were based on economic and environmental benefits from these systems whilst decision variables included how many and which type of plants to be constructed on top of the transportation issues. The exemplar case study in Turkey revealed the economic and environmental benefits of biogas to energy systems.

Seeking to prove the potential of biomass SCs of being competitive in the energy markets, De-Meyer et al., (2014), after identifying the uncertainties, presented a focused review of 71 scientific publications published for the years 1997-2012. The classification matrix provided, is structured primarily according to the mathematical optimisation methodology, secondly according to the level of decision and the corresponding analysis and above all, according to the objective function on the basis of which the Biomass SC is optimised. To that end, Mathematical programming models, heuristic approaches and multi-criteria decision analysis are reviewed, seeking to provide the optimal solution under a sustainable decision making framework. Special reference is made previously to the level of decision, i.e. operational, strategic and/or tactical, based on the selected time frame and the respective decision variables (binary, integer and/or continuous) included. All these are classified and sorted on the basis of the problem under optimisation, accounting for specific criteria (economic, e.g., transportation cost, net present value, risk on investment), energy ones (e.g., energy return, energy use), environmental (e.g., CO_2 emissions, GHG emissions, carbon footprint, global warming potential) and social (e.g., number of jobs) goals. Results state that mathematical programming models are used as optimisation tools with the objective being the economic goals under a time frame of long term, strategic decisions. MILP is proved to be the most frequent optimisation technique with a field of applicability at all decision levels, whilst, non-linear programming and integer programming are only applied to strategic type of decisions.

Next, focusing on forest biomass and its role in bioenergy competitive production (heat power and fuels), Cambero & Sowlat, (2014), introduced a review paper concerning the developed optimisation methodologies. Emphasis is given to identifying the issues associated with the planning operation and design of biomass SCs on the level of decision. On top of the generalised structure of the forest biomass SC provided, results of the analysis include environmental, social and economic implications of biomass SCs at all different levels of decisions (strategic, operation, and tactical). Moreover, emphasis is given in proving the classification according to the dimension; techno-economic, environmental, life-cycle assessments, integrated economic, social and environmental assessments; economic optimisation models; and multi-objective optimisation model. Results demonstrated that there is an increasing concern for environmental and social considerations simultaneously, on top of the need for the economic evaluation of SCs.

In the same field of integrated biomass SC optimisation, Čučeket al., (2012), introduced an MCO (Multi-Criteria Optimisation approach) for regional biomass supply chains and for the conversion of biomass to energy, accounting simultaneously for economic, social and environmental implications: Maximisation of the economic performance and minimisation of the environmental and social FPs (footprints). The model is formulated as MI(N)LP (Mixed-Integer (non)- Linear Programming). Important environmental and social FPs (footprints), like water utilisation, agricultural land footprint, energy (fossil) utilisation and water pollution and carbon footprint, are classified according to the direct or indirect impacts per SC. Results from the optimisation of the total FPs prove that compared to fossil based ones, Biomass SCs present a reduced Carbon and Energy FP, while concerning Water, Water Pollution and Land FP, the evaluation is not so prominent. This can be justified because biomass, being an agricultural-based energy source requires land intensiveness and much more water, transport needs and chemicals, when compared to fossil-based SCs.

Zhang et al., (2012) introduced a simulation model for the biomass to biofuel SC considering key activities and challenges based on a set of criteria: delivered feedstock cost, energy consumption, and GHG emissions. Challenging issues and implications of biomass to energy and biofuels have been the study objective of many researches in terms of reviewing the vast majority of works carried out in the field (Mafakheri & Nasiri, 2014) with original research studies (Akgul et al., 2012b, Dunnett et al., 2007, Kim et al., 2011, Papapostolou et al., 2011a, Sharma et al., 2013) trying to identify the optimal SC configuration by accounting this wide set of criteria.

In the same field, multi-objective optimisation has also been applied by Pinto-Varela et al., (2011) seeking to address the multiple dimensions under the numerous scales of design, towards the introduction of holistic frameworks. Concerns about climate change and security of energy supply (Giarola et al., 2012) have led towards the introduction of a multi-period models for the optimal design of first and second generation bioethanol SCs, where optimisation is undertaken in terms of simultaneous consideration of environmental and economic criteria under the technological pathways considered.

3.5.2 Hydrogen

Since being a clean resource and an efficient energy supply carrier, hydrogen SCs have been extensively examined, presenting a prominent alternative for industries, fuel stations, vehicles, fuel cells and other applications. To that end, Lee, (2014a) developed an GTAP (Global Trade Analysis Project) model in order to assess the competing relations between three widely applied generation technologies: conventional steam reforming, electrolysis, and biological and, on a second level, the end uses like electricity, gas manufacture and distribution (gas) and petroleum (refining). Under the goal of minimising the production costs, the model results demonstrated the optimal SC configuration, accounting simultaneously for LC considerations.

De-León Almaraz et al., (2014), introduced a multi-objective (economic, environmental and safety risks) and multi-period (four time periods are considered between 2020 and 2050) optimisation with special focus on the deployment of Hydrogen Suplly Chain (HSC) fuel vehicles and the respective fuel stations for a specific region in France. The strategies developed to solve the multi-period problem include a global optimisation through the ε-constraint method and a sequential optimisation through the lexicographic and ε-constraint method.

Assessing the challenges deriving from the hydrogen economy and the respective ESC, Dagdougui, (2012) made an integrated review of the modelling approaches, the objective functions, as well as the input resources and the optimisation outputs of existing works that have been carried out in the field. Results evidence that special focus of the researchers has been the planning and design of HSC on the basis of mathematical models' application with the goal being the economic optimisation. Other dimensions like environmental and social (risk, safety etch) seem to be gradually assessed as well.

Almansoori & Shah, (2006), introduced the modelling concept framework of HSCs for optimising the structure of the future hydrogen supply chain by satisfying hydrogen demand for vehicular use in Great Britain. To that end, an MILP model was formulated in respect to both minimising capital and operating costs of the HSC. As an extension to their work, (Almansoori & Shah, 2009), they proposed an MILP model for the optimal operation of HSC under a set of decisions to be supported: storage production and facilities plants in terms of number, location and capacity, flow rates and transportation links as well as production rates and inventory of the materials. All these set of decisions were made under the criterion of cost minimisation. Model implementation was carried out for Great Britain as a case study. More recently the same authors, (Almansoori & Shah, 2012), seeking to address issues of uncertainties, fuelling stations and local distribution, introduced a multi-stage stochastic optimisation problem formulated as an MILP model. Model results under the same Great Britain case study included optimal network structures for three different HSC configurations.

In addition, Dayhim et al., (2014), seeking to assess the uncertainty demand of HSC for the state of New Jersey, introduced a modelling approach for the optimal network design. The objective function of the model considered total social cost minimisation for a multi-period HSC under uncertain demand, capital costs, and storage, emission costs for production, consumption and delivery of the HSC.

Ren et al., (2013a) seeking to assess key criteria and aspects influencing stakeholders' decisions in HSCs and if possible identify the cause and effect relationships developed between them, introduced a framework of analysis of the main criteria. To that end, with special focus on economic, environmental, social and technological implications, key aspects were presented and their evaluation was carried out on the basis of a developed empirical method called "DEMATAL". Through an exemplar case study of an HSC in China, the core driving factors that were needed to be improved towards improved sustainability performance as well as specific guidelines for future decision makers in core issues were identified and suggested.

The need for an integrated framework of analysis seeking to provide an evaluation context of decisions on the basis of prioritising and ranking the HSCs in terms of sustainability performance has been analysed by Ren et al., (2013b). To that end, extension theory along Analytic Hierarchical Process (AHP) have been combined for prioritising and ranking HSCs. To this end ten HSCs previously discussed by other researchers, were analysed and re-evaluated on the basis of the newly introduced framework extension theory which was used for identifying the class of the sustainability to which each HSC belongs whilst using AHP for the calculation of weights.

Kamarudin et al., (2009) developed an MILP model for the future hydrogen SC in terms of minimising the total ESC cost. With very special consideration to the available resources, the logistics/supply network as well as the technological options and the future demand supply, optimisation was undertaken. To this end, through an illustrative case study, the optimum hydrogen delivery network, employing also truck transportation, was determined.

3.5.3 Natural gas

The increasing importance of natural gas in the petroleum industry as well as in many sectors of the energy economy (heat, power and fuel for transportation), together with the liberalisation of the natural gas industry in Europe, have initiated a wide field of research and applications (Tomasgard et al., 2007).

Hamedi et al., (2009) introduced an MINLP model, for the optimisation of the natural gas SC network, under the single objective of minimising the direct or indirect distribution costs for a multi-period time frame under a very detailed, distribution network of six levels. The model accounted for capacity constraints, continuity equations and demand satisfaction. On top of that, a hierarchical algorithm was developed by the author to provide model solutions in a decreased time.

Elia et al., (2014) developed an MILP model for strategic planning optimisation of a GTL supply network considering both operations being applicable upstream and downstream in the NGSC. In the long time frame, planning and operational (30 and 60 years accordingly) detailed information on infrastructures setup and retirement (refining planning and operation) were considered on top of economic parameters, flows and network capacity limitations and constraints.

Dos-Santos et al., (2011), with the goal of minimising the losses deriving from income and contractual penalties, developed an LP model along with a simulation approach for the optimum network management (logistics of a NGSC), accounting for the integrated NG supply network, i.e., from gas producers and transporters to the gas and energy distributor.

Özelkan et al., (2008), seeking to optimise the key design parameters affecting the terminals of the liquefied natural gas (LNG) supply chain, introduced a framework of analysis of the respective SC. An MIP model was presented on the basis of profit maximisation accounting for the major design factors of throughput, storage, number of vessels and docking capability of the LNGSC.

Kabirian & Hemmati, (2007) proposed an NLP approach for the optimisation of the natural gas network, under the goal of cost minimisation (Net present worth- NPW) for the installation and operation of the network. Model implementation supports decision making in the type and the locations of new compressor stations, routing, scheduling of the pipelines, etc. The best combination of natural gas procurement from available sources, on top of the optimum operation of the integrated network in each time step, is also examined.

Mokhatab & Poe, (2012) made an extended analysis of the environmental impacts of NG SCs in atmospheric, aquatic, noise and other specific based receivers. Special emphasis was given to the lifecycle performance of the NG and the management of the produced wastes as well as to the existing legislation and regulation in the US.

Jokinen et al., (2015) introduced the concept of small-scale distribution and to that end the authors proposed an MILP mathematical model on the basis of minimising the integrated procurement cost of the LNGSC. Under the constraint of demand satisfaction, with consideration of shorter distances and more flexible contracts, model implementation supports solutions concerning the satellite port locations, ship sizes and utilisation and customer distribution.

In the newest SCs of shale gas, Grossmann et al., (2014) proposed an MILP model for the optimal configuration of the SG infrastructures in terms of maximising the Net Present Value. Model constraints reflect the technical characteristics of the system i.e. production and demand capacities, flow balances as a function of the sizing of the plants, compressors and pipelines under examination.

Knudsen et al., (2014) introduced a large-scale MILP program for shale gas scheduling for natural-gas supply in the electricity sector. The proposed framework of analysis was ratified by illustrative case studies and solved by a Lagrangian relaxation scheme under the goal of profit maximisation. In a previous work of Knudsen & Foss, (2013), an MILP model was developed for the optimum scheduling of shut-ins of shale gas in order to maximise daily production rates. On top of the formulation of the system and optimisation in terms of operation and scheduling, significant work was included in the identification of the socio-economic impacts from SGSC implementation (Yu, 2015).

3.5.4 Petroleum based

Assessing the uncertainties involved in the petroleum organisation Al-Othman et al., (2008) developed a multi-period optimisation model to simulate and study the impacts of market prices and demand on the supply chain. The stochastic model, with the main aim of minimising all the production and logistics costs, resulted in production forecasts that were resilient to uncertainties in marketing and operational parameters, for a hypothetical SC network.

Fernandes et al., (2011, 2013) introduced a deterministic MILP model for the strategic design and planning of the petroleum SC from a downstream perspective. Applied to a real case study in Portugal, the model considered a general multi-company, multi-echelon and multi-product SC configuration. By maximising the total profits of the considered SC, model implementation provides optimal solution at the strategic level, i.e., deport locations, resource capacities, transportation modes and routes, and at the tactical level, e.g. network affectations.

Driven by the market needs, Guajardo et al., (2013) proposed a decoupled as well as an integrated approach for an SC optimisation, accounting both for the sales and the operation in a separate model. The effects of this decoupled approach (maximisation of the sales contribution minus the variable costs over the planning horizon) on the side of aided decision making concerning the company's targets and goals were extensively discussed.

Evaluating the problem of integrated resource allocation in the petroleum based SC an advanced heuristic method like the Co-evolutionary Particle Swarm Optimisation based on the Cauchy distribution was introduced by Sinha et al., (2011). The optimisation criterion under which the approach was made is the identification of the optimal SC that minimises the overall considered costs by the set of available resources and subagents available.

In an early study, Neiro & Pinto, (2004) introduced a general framework for modelling petroleum supply chains. The proposed large-scale MINLP model, actually represented a set of three elementary models: processing unit model, tank model, and pipeline model. Under the real-word problems that could be assessed by their approach, the complex topology of petroleum SC including processing units, storage tanks and pipelines in respect to customer satisfaction was optimised. Model implementation possibilities were demonstrated through a simplified supply chain network of a petroleum company having four refineries, under the profit maximisation goal.

3.5.5 Renewable based SCs (Wind, solar, geothermal)

Concluding with RES-based SCs (i.e. wind, solar and geothermal energy) the focus of researchers was set primarily to the simulation of the operational characteristics of the systems with regards to their power/heat generating potential, seeking to result an optimally sized configuration. To that end in the field of solar energy, special attention has been paid to the identification, simulation and prediction of solar irradiance (direct, diffused, beam) at an hourly-based time frame under different estimations, parameters and forecasting goals, with location based characteristics.

So, Habbane et al., (1986) seeking to identify energy produced by photovoltaic modules under certain meteorological conditions, modified a model to determine from sunshine hours for a number of stations located in hot dry arid climates. Gopinathan, (1995), tested the applicability of the clearness-index and sunshine fraction models for diffuse estimation and the effect of combining several variables into a single multilinear equation. Batlles et al., (2000), compared different models in the estimation of hourly direct irradiance values. Moustris et al., (2008), generated, using neural networks (NNs), reliable and useful time-series sets of hourly data of global and diffuse monthly solar irradiance, for location covering locations where the Hellenic National Meteorological Service measures and keeps records of climatic data in some form or another. Kaplanis & Kaplani, (2010), described a stochastic prediction model for the hourly profile of the intensity of the global solar radiation, for any day at a site. The proposed model, developed in MATLAB was validated by comparing different profiles generated for Patra, Greece. Kaldellis & Kapsali, (2011) analysed the side effects of atmospheric air pollution in the degradation of PV-panels' performance due to the deposition of solid particles. The experimental analysis was conducted in the Laboratory of Soft Energy Applications & Environmental Protection located at the campus of the Technological Educational Institute of Piraeus, Greece.

Bocca et al., (2015) made an assessment of current methodologies for photovoltaic potential, with the aim of supporting the selection of optimal sites in a given region of interest, under the case study of Italy. Kosmopoulos et al., (2015) conducted a comprehensive evaluation study assessing the reliability and verification of predictions of solar energy using ground-based solar measurements from the Hellenic Network for Solar Energy and the National Observatory of Athens network, as well as solar radiation operational forecasts provided by the MM5 mesoscale model. Villicaña-Ortiz et al., (2015) developed solar direct, diffuse and total radiation maps of the coastal zone of the Gulf of Mexico, in order to identify regions of interest for solar energy use.

In wind energy, the study objective of researchers has accordingly been the assessment of the wind energy and resource potential, seeking to forecast and possibly predict wind speed time series and characteristics for the optimal integration both in autonomous and in centralised energy systems, by mobilising simulation algorithms and forecasting models.

So in that field, Sfetsos, (2000), made a comparison of various forecasting techniques applied to mean hourly wind speed time series. Gómez-Muñoz & Porta- Gandara, (2002) used a cluster analysis technique to find the local wind patterns for modelling renewable energy systems, which strongly depends on wind loads. Poggi et al., (2003), developed a model, for forecasting and simulating wind speed in Corsica, generating 3-hourly synthetic time series for the considered sites. Tarawneh & Ahmet, (2003), tried to estimate the average wind speed in some parts of Jordan using a standard regional dependence function (SRDF) based on the concept of the point cumulative semivariogram (PCSV). Kaldellis et al., (2009a), developed a computational algorithm for the calculation of maximum wind energy penetration in autonomous electrical generation systems. Algorithm was succsfully evaluated by being compared to existing historical data as well as with the results of existing wind parks energy production.

Furthermore, with the goal being the maximisation of the wind energy penetration in the relevant market Neonakis et al., (2000) tried to estimate the starting point for substantial wind energy penetration in Greece by reviewing the time evolution of the governing parameters, concerning the economic viability attractiveness of a wind power plant in Greece, on top of an integrated cost-benefit analysis developed for the sepcifc purpose. In 2002, Kaldellis in the same field, made an integrated time-depending feasibility analysis in order to improve the reliability of the computational methods to simulate the economic behaviour of commercial wind parks in Greece. Kaldellis & Zafirakis, (2013), acknowldeging the influence of technical availability on the energy performance of wind farms made an overview of the critical factors and operational experience from wind farms around the globe while also providing a proxy prediction model for the estimation of technical availability and the determination of its impact on the annual energy yield of a wind farm.

Complementary to the investigation of autonomous power systems and communities, the introduction of energy storage systems on the side of matching demand and generation profiles, whilst stimulating the increasing need for RES larger integration, has also introduced the term of optimisation (with special emphasis on the economic dimensions of the best solution or optimal configuration among the different alternatives under examination) (Fetanat & Khorasaninejad, 2015, Fischer et al., 2014, Johnston et al., 2015, Locatelli et al., 2015, Zafirakis, 2010).

More recently, current research in the field of RES SCs has been emphasized on electricity supply (Koltsaklis et al., 2014, Osmani & Zhang, 2014) in terms of integrating different aspects and dimensions in holistic considerations of the electricity energy planning problems with all the diverse energy and fuel supply streams (Angelis-Dimakis et al., 2012) (Akgul et al., 2014, Palander, 2011, Wee et al., 2012). A specific research interest seems to be identified under the concept of islands and the respective communities in terms of fullmeeting their energy (electricity) needs in the most effective and sustainable way (Dornan & Jotzo, 2015, Duić et al., 2008, Koroneos et al., 2005).

Acknowledging the importance of existence of an integrated environment of energy and fuel SCs (both fossil based and renewables) along with the newly introduced sustainability dimensions accounting simultaneously for environmental, social, economic and technical considerations will be introduced in, Chapter 4, prior to model development of the specific electricity planning problem assessment. Special reference will be made to the introduction of sustainability dimensions both in energy problems and in relevant energy and fuel SC optimisation.

3.5.6 Multiobjective optimisation in energy planning

Seeking to underline the scope and perspective of the present research and optimisation approach of the energy planning problem modelled as an MO-MILP with binary extension as well, the special application of the MO optimisation method in the field will be listed on top of the specific SCs and models analysed above.

So, as energy and more specifically electricity planning, design and operation for meeting specific energy needs and demand priorities constitutes a composite problem whereas different resources and technological options with local characteristics, impacts and availabilities exist. The majority of the available models have been developed and formulated with special application to very specific energy systems: biomass and biofuels (Akgul et al., 2012a, Balaman & Selim, 2014, Elia & Floudas, 2014, Yue et al., 2014), hydrogen design and simulation (De-León Almaraz et al., 2013, Almansoori & Shah, 2012), optimisation models that were developed in response to the problem of meeting future demands under various uncertainties and stochastic parameters, identifying the most cost-effective solution.

However, under the wider field of energy planning, multiple and conflicting decisions that may have to be assessed at different time scales simultaneously must be addressed: investment vs operational cost, environmental performance vs economic profitability, social benefits vs technical optimality have to be equally assessed and evaluated (Lee, 2014b, Loken, 2007, Pohekar & Ramachandran, 2004, Pereira & Pinto 1991). That is the reason that significant experience has been drawn from the advanced field of process industries, by embracing notions, ideas and model applications (Barbosa-Póvoa, 2012, Kondili et al., 1993, Papageorgiou, 2009, Zhou et al., 2000).

In the field of electricity planning and optimisation, special focus has been paid on the evaluation of existing electricity supply strategies by addressing, on top of techno-economic, environmental and social dimensions as well. Following that, Akgul et al., (2014) developed a multi-objective, mixed integer nonlinear programming (MINLP) model for the optimal design of carbon negative bioelectricity supply in the UK, by minimising the total annual SC cost.

Palander, (2011) considered a multiple objective model to solve a large-scale and long-term industrial ESC scheduling problem at an energy plant in Finland with the goals investigated being the fulfilment of customer's orders, the minimisation of production cost and finally the minimisation of setup times for the energy product mixtures. Tolis et al., (2010), seeking to find the optimal mix for future electricity supply in Greece developed a Sequential Quadratic Programming algorithm for the simulation and the optimisation of the future electricity generation structure based on existing as well as on emerging technologies. The goal is the maximisation of the economic value of the system, subjected to logical, natural resources availability, environmental and social constraints.

Barteczko-Hibbert et al., (2014) developed a multi-period MILP model to help explore future pathways for electricity supply, addressing as priorities costs and carbon reduction, in two distinctive objective functions. Pérez-Fortes et al., (2012) formulated an MO-MILP (multi- objective), for the optimisation of bio-based SCs that use locally available and/or near the point of use biomass, in order to produce electricity or other bioproduct. Three main objectives are optimised: economic, environmental and social, distinctively and finally the ε-constrained method is applied.

Koltsaklis et al., (2014) presented in their work an MILP model for the optimal long-term energy planning of a (national) power generation system, with optimisation goal being the minimisation of the total power system cost under several environmental, technical and economic constraints.

In the field of multiobjective optimisation problems, typically two wide categories types of methods are applied for handling: the classical methods and the evolutionary methods. Classical methods are present almost four decades and may fall under two wide categories (Deb, 2011):

- The generating methods (where a set of non-dominant solution are generated and the decision maker chooses one solution. Here the decision maker has no a priori information about the relative importance of each objective)
- Preference based methods (where "some known preference for each objective is used in the optimisation")

As Mavrotas, (2009) analyses after the work of Hwang and Masud, (1979),"*Multi-Objective Mathematical Programming (MOMP) methods can be classified as a priori, interactive and a posteriori, according to the decision stage in which the decision maker expresses his/her preferences*".

Further classification following includes:

- Non-preference methods (where no a priori information about the preference is known and heuristic method is used to obtain optimal solution- here no emphasis is given to find multiple Pareto optimal solutions)
- A priori methods
- Posteriori methods (where preference based information for each objective is used and the goal is to generate a set of Pareto-optimal solutions)
- Interactive methods (where preference based information for each objective is used progressively through optimisation in order to generate a set of Pareto-optimal solutions)

In the *"a posteriori"* /generation methods the set of efficient solutions are sufficiently represented and then the decision maker is involved in terms of selecting among them, the most preferred one. The generation methods are the less popular due to their computational effort (the calculation of the efficient solutions is usually a time consuming process) and the lack of widely available software. However, they have some significant advantages: the solution process is divided into two independent phases: First, the generation of the efficient solutions and subsequently the involvement of the decision maker when all the information is on the table. In general, the most widely used, generation methods are the weighting method and the ε-constraint method.

In the present approach the weight sum method is applied for handling the energy planning problem under consideration by scaling the set of techno-economic, environmental and social objectives into a single one based on author applied weights. With regard to the criticism about weights assignment, under the introduction of the notion of sustainability into electricity planning and operation, the three functions are considered of equal importance i.e. assigning a weighting factor of 0.333 to each one of them.

In the advantages of the proposed approach one may include the simplicity of the implementation and the transparency /easiness for results' interpretation. In the disadvantages, the subjectivity of the decision maker to provide the weights. Uncertainties are meant to be assessed with sensitivity analysis in Chapter 6.5.

In Chapter 4 following, the integrated environment of energy and fuel SCs will be analysed in respect to the basic concepts and indicators applied in their evaluation.

CHAPTER 4: THE INTEGRATED ENVIRONMENT OF ESC

In this chapter the integrated environment of evaluating alternative energy and fuel SCs will be analysed. The type of parameters and indices selected in the evaluation, their origins and the multiple stakeholders involved in different levels of decisions will be described.

4.1 Introduction

During the past few years, organisations and decision makers as well as individual stakeholders have tried to incorporate in their decision-making multiple issues, accounting simultaneously for technical, environmental and social aspects, conflicting in many cases. As discussed previously, initiated from SCM, the integrated evaluation was primarily introduced along with the concept of GSCM in respect to minimising the environmental impacts of the SCs considered. At the same time, assigned mainly to firms, considerations towards the social issues and impacts of the SC, Corporate Social responsibility – CSR were introduced and helped the GSC to evolve to SSC.

This holistic contemplation under the concept of SC as Ahi and Searcy state (2014), has been extensively studied and debated from the scientific community, seeking to build a consensus around the term of sustainability in alliance with SC evaluation i.e. which are the sustainability dimensions that maybe equally applied in the evaluation of SCs and how these different concepts and indices maybe appropriately assigned a quantifiable nature (Seuring & Müller, 2008, Seuring et al., 2008).

However, even after a significant number of publications existing in the field, the indices applied in the performance assessment of the SCs, are in their majority still case-specific, following the characteristics of the SC under consideration, with the most commonly measures being identified in the field of environmental air quality evaluation (i.e. air emissions, carbon footprint etc).

Considering more holistic analyses, the bibliography still remains limited and concentrated around either implications of the SC in the environment (i.e. water and energy resources utilisation, land intensiveness etc), or in a very narrow number also accounting for social and techno-economic implications as well. This can be reasonably justified recognising the fact that, at the moment at least, in the field of energy production and supply, energy pricing in its majority still reflects the techno-economic parameters, and in a very small percentage only environmental implications.

Thus, in the interest of advising on alternative energy policies under a strong framework of assets, system's progress must be monitored towards sustainability, within the overall economic, social and environmental framework as prescribed. In that direction many studies have been conducted seeking to build a consensus around the concept of integrated sustainability. Despite the fact that a wide range of relevant indicators exist, agreement on the total sustainability is almost impossible to find, as externalities i.e. the society, might play a deterministic role in the decision of integrating alternative and renewable ESCs (Ribeiro et al., 2011). In the present work, the evaluation of alternative energy and fuel SCs for power planning will be examined with consideration of the multi-dimensional framework (as illustrated in Figure 33) applied in the energy systems. Before proceeding to that, the basic concepts of sustainability and a brief historical background will be presented in the following section, to set the fundamentals of the analysis.

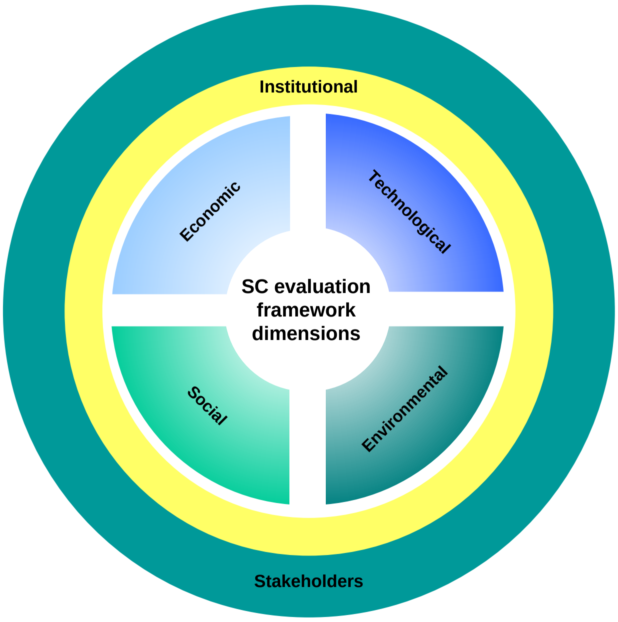


Figure 33: The proposed SC evaluation framework for energy supply

4.2 Basic Sustainability Concepts

Typically, the design and operation of energy and fuel SCs, both at strategic and operational level, was carried out under the principles of technical efficiency and economic viability, assigning per case performance indices like energy input-to-output ratio. Nevertheless, the need to assess multiple implications in energy and fuel SCs has led the research community to produce a wide range of debating studies on the application of sustainability principles.

The starting point maybe identified back in 1992, when the Earth Summit recognised the need for countries to develop sustainability indicators so as to have a framework of assisting energy decision making. This was communicated by Chapter 40 of Agenda 21, which initiated countries and organisations to develop indicators of sustainable development. In 1995, the Commission on Sustainable Development (CSD) approved a "Work Programme on Indicators of Sustainable Development", with the first two sets of CSD Indicators of Sustainable Development developed between 1994 and 2001 (United Nations, 2007). This set of indicators has been extensively tested, applied and used in many countries as the basis for the development of national indicators of sustainable development.

In 1995, the United Nations Department of Economic and Social Affairs (UNDESA) produced a set of sustainable development indicators assessing the "*annual energy consumption per capita, intensity of energy use and share of consumption of renewable energy resources*" (Vera & Langlois, 2007). This effort was supported and followed by International Atomic Energy Agency (IAEA) that instigated a long-term programme on Indicators for Sustainable Energy Development (ISED) in 1999 in cooperation with various international organisations and some Member States of IAEA. Project results were presented in 2001 at the CSD-9 (Table 1). *To provide a consistent format both of methodology and information sheets, country-related workshops and training were applied in a nation-based approached followed by a testing process (on a voluntary basis) involving t*wenty-two (22) countries covering all regions of the world (United Nations, 2001).

Table 1: Key themes suggested by CSD testing country priorities

Social	Environmental
Education	Freshwater/groundwater
Employment	Agriculture/secure food supply
Health/water supply/sanitation	Urban
Housing	Coastal Zone
Welfare and quality of life	Marine environment/coral reef protection
Cultural heritage	Fisheries
Poverty/Income distribution	Biodiversity/biotechnology
Crime	Sustainable forest management
Population	Air pollution and ozone depletion
Social and ethical values	Global climate change/sea level rise
Role of women	Sustainable use of natural resources
Access to land and resources	Sustainable tourism
Community structure	Restricted carrying capacity
Equity/social exclusion	Land use change
Economic	**Institutional**
Economic dependency	Integrated decision-making
Energy	Capacity building
Consumption and production patterns	Science and technology
Waste management	Public awareness and information
Transportation	International conventions and cooperation
Mining	Governance/role of civic society
Economic structure and development	Institutional and legislative frameworks
Trade	Disaster preparedness
Productivity	Public participation

Adapted from: United Nations Department of Economic and Social Affairs, *Testing the CSD Indicators of Sustainable Development: Interim Analysis: Testing Process, Indicators and Methodology Sheets,* Technical Paper prepared by the Division for Sustainable Development, 25 January 1999; and United Nations Department of Economic and Social Affairs, *UN CSD Theme Framework and Indicators of Sustainability,* Final Draft, PriceWaterhouseCoopers for Division for Sustainable Development, November 18, 1999.

In 2002, the IAEA led the indicators project which was classified as an official partnership initiative of the World Summit on Sustainable Development (WSSD). The international partnership initiative on ISED was conducted by the IAEA in cooperation with UNDESA, the International Energy Agency (IEA), the Statistical Office of the European Communities (Eurostat) and the European Environment Agency (EEA), i.e. organisations, which are recognised as world leaders in statistical analysis and in the development of energy and environmental indicators (Vera et al., 2002, Vera & Langlois, 2007).

The aim of the developed set of indicators was to guide the implementation of actions urged at the WSSD (IAEA-International Atomic Energy Agency, 2005): (i) to integrate energy into socioeconomic programmes, (ii) to combine more renewable energy, energy efficiency and advanced energy technologies to meet the growing need for energy services, (iii) to increase the share of renewable energy options, (iv) to reduce the flaring and venting of gas, (v) to establish domestic programmes on energy efficiency, (vi) to improve the functioning and transparency of information in energy markets, (vii) to reduce market distortions and (viii) to assist developing countries in their domestic efforts to provide energy services to all sectors of their populations.

As Vera & Langlois, (2007) analyse, energy and sustainability indicators were not purely statistically oriented but in their definition more complicated relationships revealing causal interactions, trade-offs and implications between the systems under examination, that maybe incorporated as well. To that end, international organisations, experts, policy makers and academics have started developing guidelines and methodologies on top of the set of the existing indicators, representing the positive or negative impact of energy use (and/or its absence) on economy, society and on the environment too. In the most general form, sustainability sets three basic pillars of development: economy, environment and society. Therefore, in the choice of ex-ante evaluation of different ESCs, resources and technologies one should account simultaneously for the social, environmental and economic dimensions of the under selection options:

- Economic sustainability: efficiency of the economic system /avoid sectorial imbalances
- Ecological/ Environmental sustainability: conservation of the natural resource /non over exploitation/ non depletion of non-renewable energy recourses / maintain ecological equilibrium of the system
- Social and Political sustainability: fairness in distribution and opportunity and equal provision of social services.

In the following sections some very basic definitions for sustainability will be provided as cited in IAEA report on "*Energy Indicators for Sustainable Development: Methodologies and Guidelines*" (IAEA, 2005), in European Communities, 2009, *"Sustainable Development Indicators. Overview of relevant FP-funded research and identification of further needs"* (European Commission, Directorate-General for Research, 2009[2]), in International Institute for Sustainable Development, *"Creating Indicators of Sustainability, A social approach"*(Miller, 2007) and in United Nations

[2] The full list of Sustainable Development Indicators is quoted in Appendix A1

Global Compact (2010), *"Supply Chain Sustainability A Practical Guide for Continuous Improvement",* (United Nations Global Compact, 2010).

Economic Sustainability

Economic sustainability is about achieving economic growth while protecting and safeguarding the environment and the individuals that live in. It is the result from the interaction between the social factors and the environment which is necessary for the long term existence of organisations. *It is also about the efficient and sustainable utilisation of recourses producing positive outcomes while minimising environmental consequences. Key* indices used on the side of the economic dimension evaluation are: taxation and subsidisation, pricing, security and diversity.

Environmental Sustainability

Environmental sustainability is about determining the impact of the energy system and in our case of the energy supply system in terms of positive or negative effect on the environment i.e. land, water (fresh and marine), air quality and aesthetic impacts. These impacts are determined by the scale and the type of production system as well as from the natural receiver that it is being affected: an PV or wind park may be claimed to be spoiling a country side's scenery, biofuels maybe blamed for deforestation and land degradation, fossil fuel plants for GHG emissions, etc. The main issues around environmental sustainability include global climate change, air pollution, water pollution, wastes, land degradation and deforestation, addressed also in a lifecycle perspective.

Social Sustainability

Social dimension measures the impact that (energy) services may have on social well-being. It is very important because it reveals the implications that a task may have in the human environment in terms of poverty, employment opportunities, education, community development and culture, demographic transition, indoor pollution and health, as well as gender and age-related implications. Social ISED describe issues related to accessibility, affordability and disparity in energy supply and demand. In rich countries, modern energy services (lighting, heating, cooking, etc.) are almost universally available. Today it is encouraged for Social Impact Assessment (SIA) to include other sustainability pillars and for Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA) to incorporate social issues as well.

Institutional Sustainability

A rather new dimension on the side of evaluation of sustainability is the institutional, assessing the existence, adequacy and efficacy of the institutional framework to support the energy systems. "*Institutional indicators are useful for linking and addressing the response actions and policy measures designed to influence trends in the social, economic and environmental dimensions*" i.e. the effectiveness of a national sustainable energy development strategy or plan, energy statistical capacity and analytical capabilities, investments' implications on research and development. Indicators in this dimension are the most difficult to quantify and define. They serve as a screening filter, a feasibility measure of actions examined.

4.3 Key Sustainability Indicators

"Generally speaking, an indicator is anything that gives an indication to its reader of a key feature or state of a human or environmental system, providing valuable information quantitative in most of the times on the side of decision making" (Miller, 2007).

As concluded in the review report of European Communities "*Sustainable Development Indicators. Overview of relevant FP-funded research and identification of further needs* "(European Commission, Directorate-General for Research, 2009), of over 40 such research FP6 and relevant FP7 projects which, either as a part of their work or as the main focus of their work, developed indicators which are relevant to measuring progress on the Sustainable Development Strategy (SDS):

- *Climate change and energy* with special emphasis and ongoing work: end-use energy efficiency and savings; monitoring the influence of sustainability criteria for biofuels; and the integration of adaptation to and mitigation of climate change into policies.
- *Conservation and management of natural resources*: fisheries and biodiversity.
- Social indicators including for *public health, social inclusion and demographic changes and migration*
- Indicators to measure progress on the SDS key challenge of *global poverty and sustainable development*
- Indicators for the many *cross-cutting objectives i.e. 'good governance' which require special attention in their definition and interpretation*

The list developed by the European Commission, includes some sets of indicators, such as Eurostat's Sustainable Development Indicators (SDIs) which been specifically designed to monitor this progress while others, such as those used in DG Environment's Environmental Policy Reviews, have focus on certain aspects of sustainable development, i.e. the environmental dimension. These indicators were formed under 10 themes which represent key /strategic issues and challenges and subthemes to optimally reflect operational objectives and actions.

Additionally, depending the level of decision to be assisted, the indicators are built as a three-level pyramid, with each level representing the Sustainable Development Strategy distinctive objectives (overall objectives, operational objectives, actions) and also respond to different kinds of stakeholders. Level 1 indicators (overall objectives) → Level 2 indicators (operational or priority objectives) → Level 3 indicators (implementation actions). The complete set of indicators "Socio-Economic Development" are listed in Appendix A2.

Moreover, setting the fundamentals for European Commission, back in 2005, IAEA developed a set of 30 Energy Indicators for Sustainable Development (EISD), classified into three dimensions (social, economic and environmental) further divided into 7 themes and 19 sub-themes. It is worth noticing that some indicators can be classified in more than one dimension, theme or sub-theme, given the numerous interlinkages among these categories. Appendix A3 lists the initially developed energy indicators for sustainable development after the IAEA report (2005).

4.4 Assessment of economic, social and environmental values in the ESC optimisation

Contemporary decision-making must be undertaken accounting all the possible alternatives in respect to each specific case-study characteristics. More particularly in energy planning, the selection between technological options, resources or feedstock availability, production pathways as well as end consumers' satisfaction (in terms of priority) and product final delivery, needs to be assessed under an objective framework of approach, identifying the possible trade-offs both in a strategic and operational perspective. So, due to the competitive character of the conflicting goals and decisions to be undertaken in each step of the SC, assisted decision-making is required. The need for assigning a sustainable dimension in the SCs under evaluation has introduced the use of sustainability indicators, as an evaluation measure or a performance index of SCs.

Proceeding to this frameworkof holistic analysis, the types of indicators to be used in each respective case, are meant to consider systems boundaries and operational characteristics. Under the level of examination and the stages of the SC considered, three distinctive levels may be acknowledged as illustrated in Figure 34:

- Supply side (inbound and outbound logistics and production level)
- Supply and demand side (raw materials production, product process, delivery and consumption to the end customer) – SC level
- Accounting as well Life-Cycle Assessment (LCA) mainly focused on environmental implications and resources uses at the end of their lifetime (LCA- level).

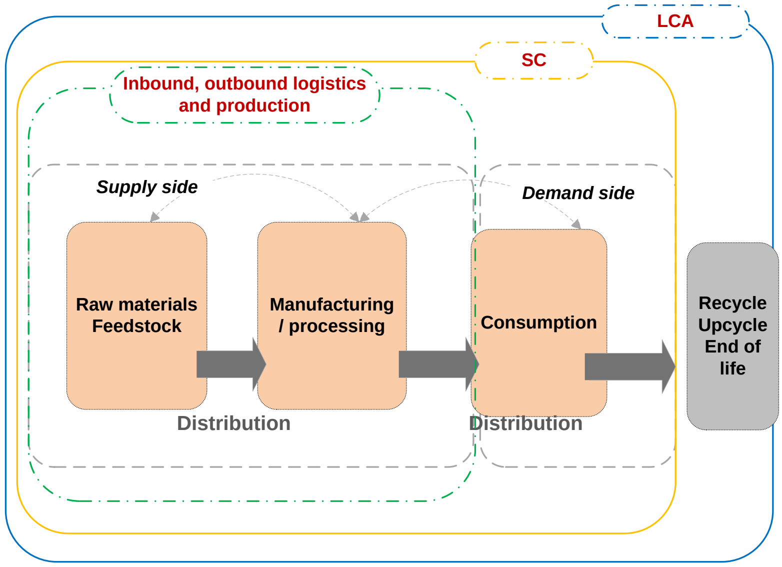


Figure 34: Different levels of SCs' analyses

In the present work, the system boundary to which the analysis is delimited is the SC level (Figure 34). However, seeking for an integration of a Life-Cycle perspective as well, environmental footprint of the SCs for power planning, as a measure of their impact in the environment in a wider than the strategic time horizon, will be introduced.

Proceeding to the identification of the possible implications in the environment, under the example of a product and/or fuel based SC in an input/output analysis, from a top down perspective, incorporates: energy and other types of resources in the input side, and wastes, emissions and product delivery on the output side (Figure 35).

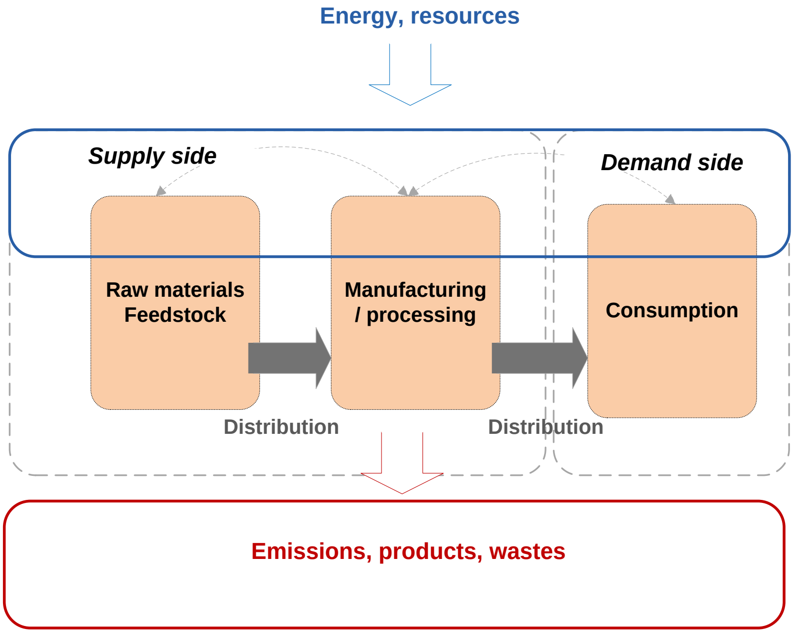


Figure 35: Typical outputs of a product- based SC

Looking more closely for a specific SC paradigm (i.e. of the biofuels' SC) the output of each stage, both indicators and impacts, are not only reflecting immediate effects but also long-term ones like possible acidification and eutrophication, environmental effects, land carbon loss (Figure 36).

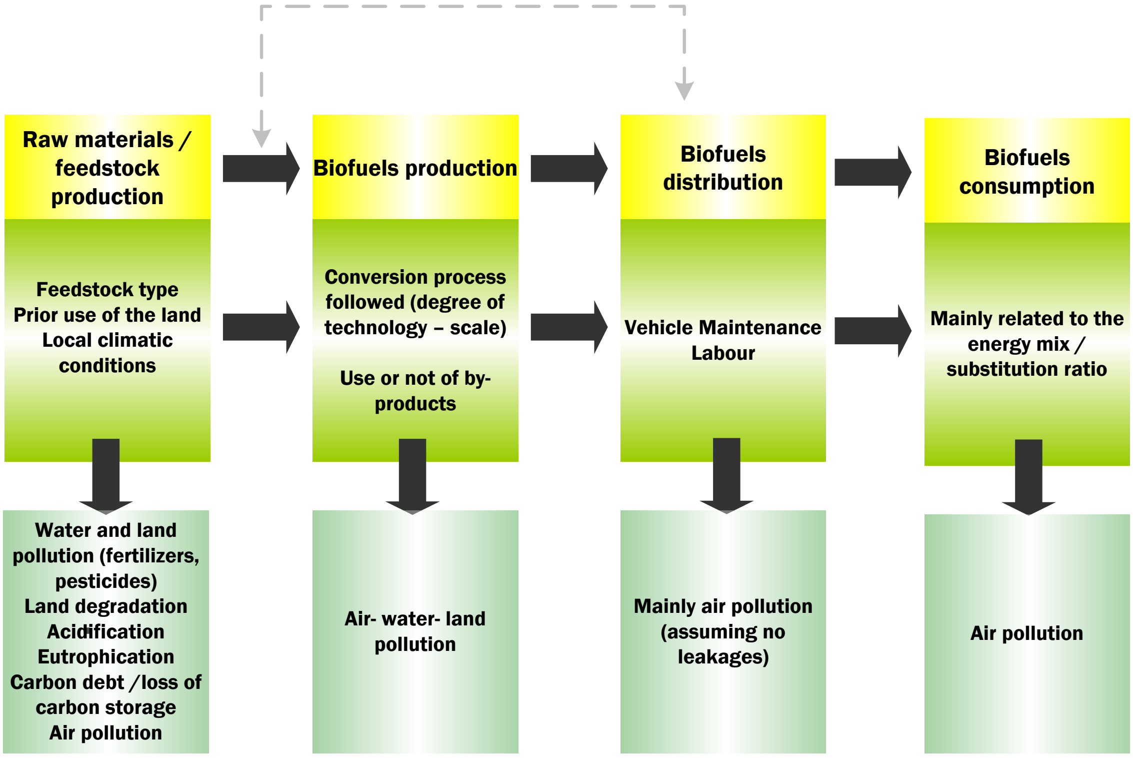


Figure 36: The biofuels SC specific example (Papapostolou et al., 2008)

In the field of electricity SCs' evaluation, the indicators selected are meant to address the specific issues occurring in the energy planning, seeking to respond to the following questions:

- Which is the optimum fuel mix to be utilised?
- Which plants should be used?
- If new infrastructures are required in which technologies should we invest?
- Which is the most sustainable power generation option?
- What the limitations concerning the different dimensions of the examined configuration and dimensions?
- Should the state promote some power generation options over others?

With that view, the sustainability indicators that will be used in the present research, follow in their categories the three basic distinctions as identified and studied both by the European Commission and the IAEA, but they are content-oriented to fit the energy and fuels SC's evaluation. More precisely we have:

Environmental indicators

Environmental indicators acknowledge the impact of the SC on the environment, under then main impacted area which is air quality. Other dimensions like land utilisation and footprint will be incorporated as constraints of the problem under consideration.

Social indicators

Social indicators are used in order to reflect the impact of the SC in the social environment. In this set (of indicators) both long and short term indices will be present addressing the positive micro-social benefits of new power generation projects on a specific area i.e. population enrichment of an area due to jobs creation resulting increase of standard of living and quality of life. Macro-social indicators will also be used to reflect the macro-economic penalties, mainly at country-level that occur from currency exchange losses of the imported fuels for electricity generation. Additional social issues like health effects on population, are indirectly assessed via environmental (in LCA terms footprints).

Economic indicators

Economic indicators are designated to reflect the system economic performance, including the capital investments, the operational and maintenance costs, labour costs and energy consumption cost. On the income side the energy selling price is considered. As one may recognise some indicators may interlink more than one dimension of evaluation i.e. jobs creation → GDP increase, health effects resulting from long term environmental impacts. So in each case the indicators selected and their characterisation and classification may entail a subjective basis due to the complementarity of specific parameters and indices. Other types of energy and fuel SC indicators reflecting technical efficiency and resources utilisation, like fuel, water, and other raw materials utilisation ratio, will be incorporated in technical limitations and conversion efficiency of the model under consideration. In Appendix A4, an analytical Table, concering the qualitative and quantitative indicators applied in the evaluation of Energy and fuel SCs is listed.

4.5 Sustainability indicators selected for our case

The indicators selected should reflect the sustainability concept with respect to the SCs under examination. That means that the selected indicators should reflect the problem characteristics well as the criteria to be optimised under the energy planning concept, and that they can be assessed in a quantitative basis so as to reflect the performance measures of the set of the available alternative options. Also a very important attribute is that the indicators can be: a) time-flexible reflecting all the different time scales embedded in energy decision making, b) multi-level adaptable being easily equally applied both to strategic levels of decisions but on operational types of problems as well, and c) on top of all of generic nature so that they can serve on the evaluation of multiples energy and fuel SCs.

In the present approach, taking into account the list for sustainability criteria developed by the European Commission (2009), a generic set of indicators is used which will be presented in the next section. This list of sustainability criteria has the flexibility to be applied in multiple SCs and systems, assigning in each case, under the level of decision undertaken (strategic, tactical and/or operational) and the time-frame appropriately formed values. The main axes of priority of our work include:

- Economic (investment, operational and maintenance costs, incomes from produced electricity being sold to the network operator, electricity purchase cost from the storage station as well as from the interconnection option)
- Environmental (Positive (minimum) environmental footprint of each ESC compared to an environmental friendly ESC option)
- Social (Employment yield, as a micro- social benefit and security of energy supply and exchanges losses in terms of macro security consideration)

All the sustainability indicators selected are appropriately quantified under the functional unit of the system under consideration, the electric kWh produced. Some indicative works in the field, are given in Table 2. More precisely in Table 2 research papers (sorted by citation order) are classified according to the type of SC examined (biomass, wind, NG etc), the type of criteria (technical, economic, social, environmental), the type of the analysis and values provided (qualitative or quantitative) and finally other type of information (under the column other) that maybe useful for future readers. This information will be used in parameters value assignment and determination as cited in Chapter 5, problem definition and model development.

Table 2: Economic, Technical, Environmental and Social criteria applied in the evaluation of Energy and Fuel SCs

Author (s)	Citations	SC, or reference	ECON	TECH	ENV	SOC	QuaNT	QuaLT	Other	Keywords
(Varun et al., 2009)	141	Electricity, wind, PV, solar-thermal, biomass, hydro	✔	✔	✔		✔		Framework	Sustainable development; Environmental impacts; Emissions; Energy; LCA
(Rentizelas et al., 2009)	138	Biomass	✔	✔						Logistics; Biomass storage; Multi-biomass; Biomass supply chain; Energy exploitation; Agricultural biomass Contents
(Singh et al., 2009)	115	Generic	✔	✔	✔	✔		✔	Review	Sustainable development; Sustainability indicators; Index; Composite index; Ratings
(Vera & Langlois, 2007)	95	Generic	✔	✔	✔	✔		✔	Framework	Energy accessibility; Energy indicators; Energy intensities; Energy use; Environmental impacts; Sustainable development
(McCormick & Kåberger, 2007)	90	Bioenergy						✔	Framework	Bioenergy; Biomass; Renewable energy; Sustainable development
(Moldan et al., 2012)	77	Generic	✔	✔	✔	✔	✔	✔	Framework	Sustainable development indicators; Environmental sustainability; Performance indicators; Target setting; Proximity to target assessment
(Yue et al., 2014)	58	Biomass, bioenergy, biofuels					✔		Framework	Bioenergy; Biofuels; Mathematical programming; Multi-scale modeling; Supply chain modeling
(Dunnett et al., 2007)	38	Biomass	✔	✔						Bioenergy; heat; optimisation; scheduling; supply chain; systems analysis
(Patlitzianas et al., 2008)	38	Criteria for SDI selection						✔	Framework	Energy indicators; Energy policy; Sustainability
(Kaldellis et al., 2009a)	35	Wind, storage	✔	✔			✔			Autonomous wind power system; Optimum system sizing; Remote consumers
(Papapostolou et al., 2011a)	32	Biofuels	✔	✔			✔			Transportation fuels; Biodiesel conversion; Integrated biofuels planning
(Sharma et al., 2013)	30	Biomass		✔	✔			✔	Review	Bioenergy; Biofuels; Biomass; Biomass supply chain; Logistics; Mathematical modeling
(Kaldellis et al., 2009b)	21	PV, storage	✔	✔			✔			Autonomous electrical network; Electricity generation cost; Energy storage; Hybrid system; Photovoltaic generator
(Tsai, 2010)	20	Wind, solar, hydro, bioenergy	✔		✔		✔			Sustainable development; Energy indicator; Renewable energy; Energy policy
(Georgakellos, 2010)	18	NG, Lignite, oil					✔		External Cost	External cost; Electricity prices; Climate change; Thermal power plants; Greece
(Tolis & Rentizelas, 2011)	16	Coal, Oil, NG, lignite, NG, biomass, PV, wind, hydro (electric / pumped storage)	✔	✔	✔	✔	✔		Framework	Electricity prices; Power sector portfolio; Optimisation; Operational research; Emissions trading
(Palander, 2011)	14	Electricity	✔	✔				✔		Decision-support systems; Information logistics; Peat tax; Feed-in tariff; Energy efficiency
(Grave et al., 2012)	12	Geothermal, biomass, wind , PV, water		✔		✔				Supply adequacy; Integration of renewable energy sources; Power generation
(Treyer et al, 2014)	7	Fossil and renewable technologies	✔	✔	✔		✔			Electricity production; Life cycle human health impacts; Life cycle assessment
(Mainali & Silveira, 2015)	4	Wind, solar, biomass, hydro, diesel								Energy technology sustainability index; Indicators; Composite indicators; Principal component analysis; Electrification
(Maxim, 2014)	4	Coal, NG, fuel cell, Hydro (small-large), wind (on-offshore), solar, solar –thermal, biomass, nuclear	✔	✔	✔	✔	✔		Review	Electricity generation; Sustainable development; Multi-criteria decision analysis
(Kaldellis and Zafirakis, 2013)	2	Wind, storage	✔	✔			✔			Wind turbines; Downtime period; Maintenance and operation
(Gibon and Hertwich, 2014)	1	Wind (offshore-onshore), PV, CSP, hydro, coal , NG,			✔					na
(Barteczko-Hibbert et al., 2014)	0	Fossil and renewable technologies	✔	✔	✔		✔		External costs	Energy planning; Mixed integer linear programming; Optimisation; Life cycle assessment; Climate change; Scenario analysis
(Sharma & Balachandra, 2015)	0	Electricity	✔	✔	✔	✔	✔	✔	Review, case-study	Electricity system; Sustainability indicators; Sustainable energy; Electricity sustainability index

ECON:Economic, TECH: Technical/technological, ENV: Environmental, SOC:Social, QuaNT: Quantitative, QuaLT:Qualitative

CHAPTER 5: PROBLEM DEFINITION: SYSTEM REPRESENTATION AND MODEL DEVELOPMENT

In this chapter the basic components of the proposed evaluation framework of alternative energy and fuel SCs will be introduced. After the examination of the basic sustainability concepts and indicators widely applicable in the field, the system representation as well as the mathematical model formulation will be presented. Basic components of the evaluation framework are the representation of the SCs along with the appropriately formulated mathematical model. On top of the selected and analysed sustainability indicators described above, the special framework implementation or adaptation of a real case energy planning problem concerning an isolated consumer or community will be introduced as well.

5.1 Generic representation of alternative energy and fuel supply chain

As energy and fuel SCs are multi-structured, multi-dimensional and they operate under different time intervals, there is a need for uniform representation and a general framework for their evaluation. When examining energy SCs in a top down perspective, they present significant resemblances with chemical plants' production chains in terms of topology, scheduling – based on demand driven prerequisites, the production processes and the optimisation goals (i.e. maximisation of profit, efficiency, or social welfare maximisation etc).

To that end, identifying some very specific elements one may say that we are dealing:

- with multiple resources or feedstock,
- multiple process technologies/conversion efficiencies to produce multiple products
- under specific demand and efficiency constraints

When producing multiple products, there is a need for providing a simplified conceptualisation of the term ESC and fuel. In respect to that, the Recourse-to-Task Network (RTN) representation is adopted taking into account all the extended previous experiences and the number of research papers (about 500) following similar topologies for evaluation. Looking at the background of the work, as acknowledged by Kondili in 1988 and 1993 respectively (Kondili, 1988, Kondili et al., 1993), batch processes in multipurpose plants can be modeled and optimised in terms of State-Task Networks (STN), where both individual batch operations "tasks" and feedstocks, intermediate and final products "states" can be explicitly included as network nodes (Figure 37). The term plant is very similar to the concept of the SC: some plants in chemical industries operate as multi-product plants, where the products follow exactly the same production pathway (i.e. the biofuels SC) and as multipurpose plants in which different products may follow different production pathways (i.e. the biomass SC).

In 1994 Pantelides (Pantelides, 1994) presented an integrated framework based on an RTN representation of the process in which all resources (equipment items, storage, utilities etc.), are treated uniformly (Figure 38). This generic approach facilitates the conceptualisation of energy and fuel SCs, taking account that both complicated production features and differentiated SC activities exist, all in a unified and consistent manner as illustrated in respective examples in Figures 39 and 40. Therefore, the key idea for the proposed representation is to identify what is a task (process) and what is a resource and how these elements are linked under some very critical parameters of consideration:

- The extent of the planning horizon;
- the availability of each feedstock resource;
- the technological know-how and the available options;
- the conversion efficiencies;
- the energy demand requirements;

In Table 3 some basic elements for the proposed superstructure of a generic representation of the energy and fuel SCs are identified with the experience of STN and RTN works.

Table 3: Key elements- annotation of the proposed representation

	STN	RTN	RTN in energy and fuel SCs
States / Resources (denoted by a circle)	Refers to product states (Raw material, Feedstock Intermediate products Final products).	Material or energy streams involved in the provision of energy (or other) i.e. gas, electricity, heat, potable water, waste water, municipal solid waste and CO_2.	Fuel or energy or power to be converted from one form to another (i.e. natural gas, oil, hydro-power, wind energy, solar to power energy, biomass to power, coal, geothermal energy).
Tasks (denoted by a rectangle box)	Production and processing processes (i.e. a physical or chemical operation, such as reaction, heating and separation).	The technologies represent any process that can convert a set of input resources to a set of output resources. A typical technology would be a CHP unit, which primarily produces high-quality heat, electricity and CO_2 from an input resource, such as natural gas. Technologies are also used to represent storage and transport of resources.	Process / production/ conversion technologies (i.e. kinetic energy to mechanical energy in wind turbines). Energy storage technologies.

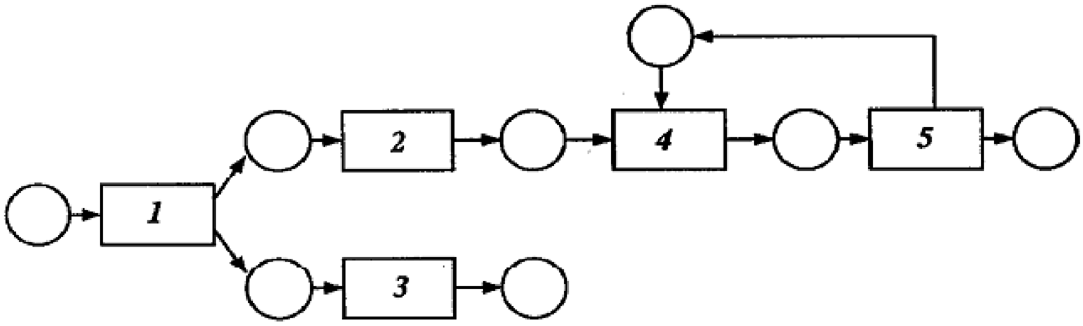


Figure 37: State-task network representation of chemical processes (Kondili et al., 1993)

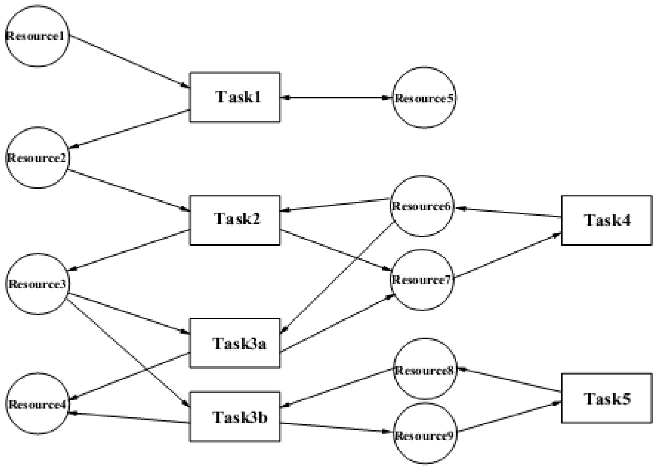


Figure 38: Resource-task network process representation (Pantelides, 1994)

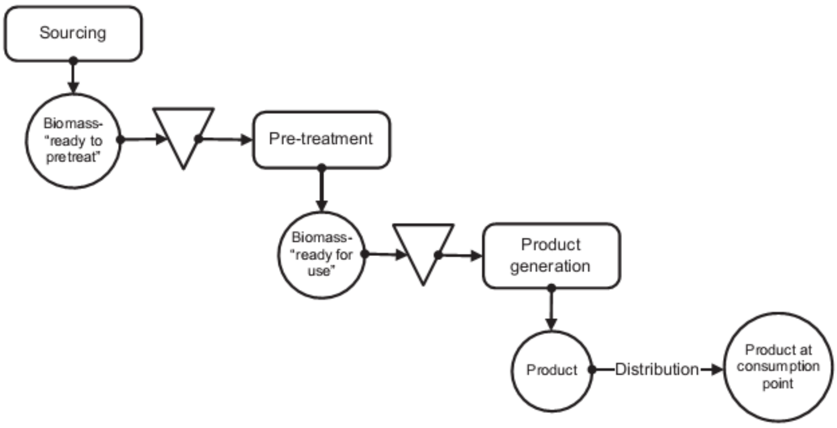


Figure 39: General scheme considered for a Biomass SC (Pérez-Fortes et al., 2012)

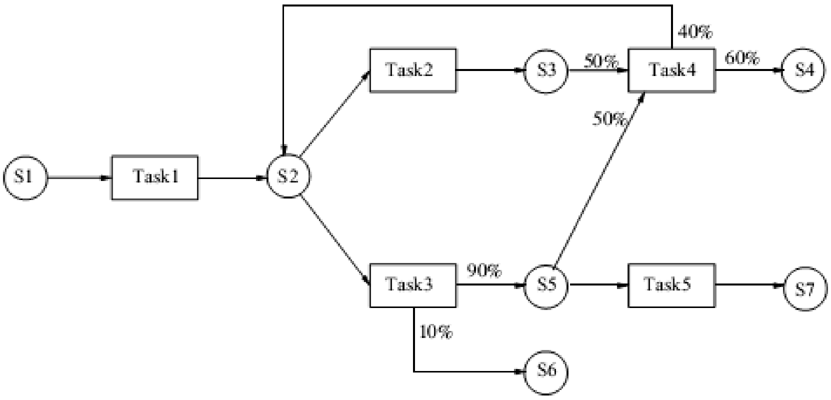


Figure 40: State-task network process representation with fraction of states (Floudas & Lin, 2005)

When the fraction of a state consumed or produced by a task, if not equal to one, is given beside the arch linking the corresponding state and task nodes

So, acknowledging that in the energy and fuel SCs field there is as a special focus on the resources identification, utilisation / process (conversion technology) and end-consumption the RTN representation is equally adopted; we consider a very simple and generic representation which focuses on the basic resources (energy, fuels, raw materials), on a single end product (power to grid) and on multiple conversion technologies (Figures 41, 42). However, this simplified concept may equally well apply to any resource in energy /fuel SC.

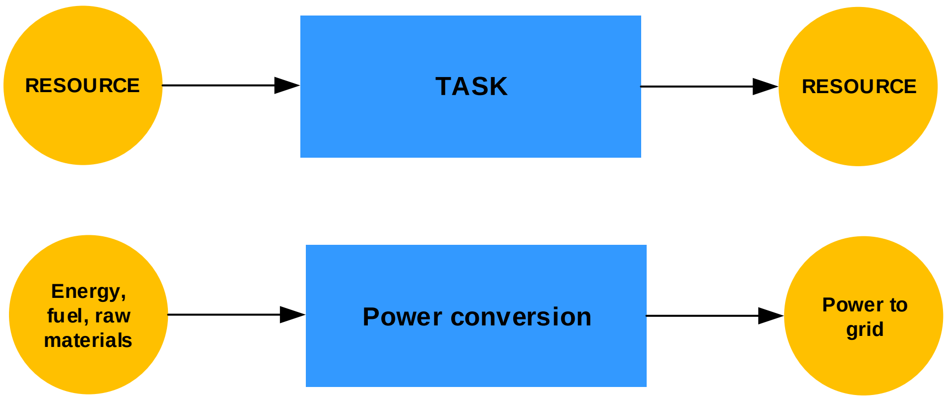


Figure 41: The proposed superstructure of Energy and Fuel SCs

More specifically for each of the examined energy and fuel SCs the generic representation for electricity production is illustrated in Figure 42.

Figure 42: Generic representation of Energy and Fuel SCs

For the very specific case of energy storage incorporation that is applicable to Hydropower and RES-based electricity generation (which could be potential energy for hydropower, or compressed air energy, or chemical energy in a battery) the generic RTN representation includes another task that represents the operation of the storage namely the charging and discharging rate, according to the system's requirements (Figure 43).

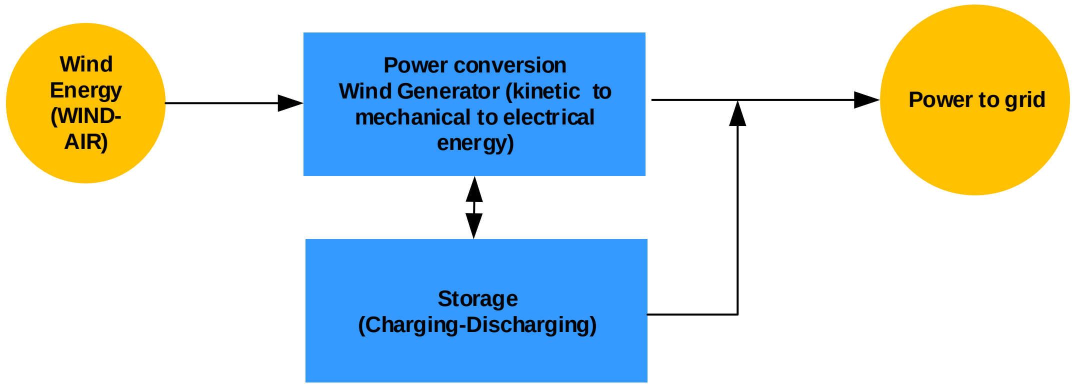
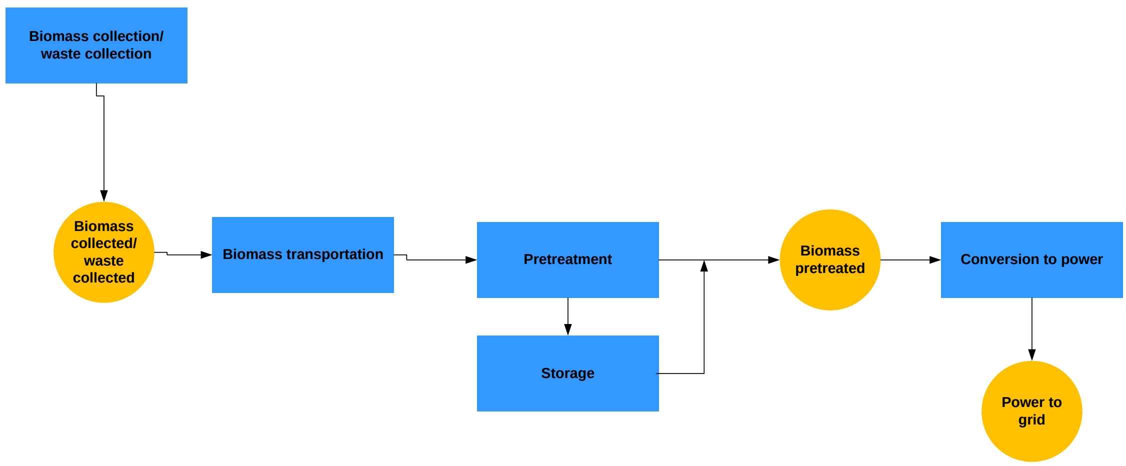


Figure 43: The storage operation under the example of wind-to-power RTN

Acknowledging the benefits of RTN system representation is that it may address a wide number of tasks and resources, equally simple. As one may point out from the illustrations in Figure 44, very specific characteristics (tasks and resources) can be introduced in the energy and fuel SCs, considering explicit resources in process for each one: i.e. for biomass SC in the tasks we have the feedstock or waste collection, biomass transportation, treatment and storage, and finally conversion to power, whereas in the case of wind energy for example there is just the task of wind energy conversion to power and energy storage prior to power being transmitted to the grid.



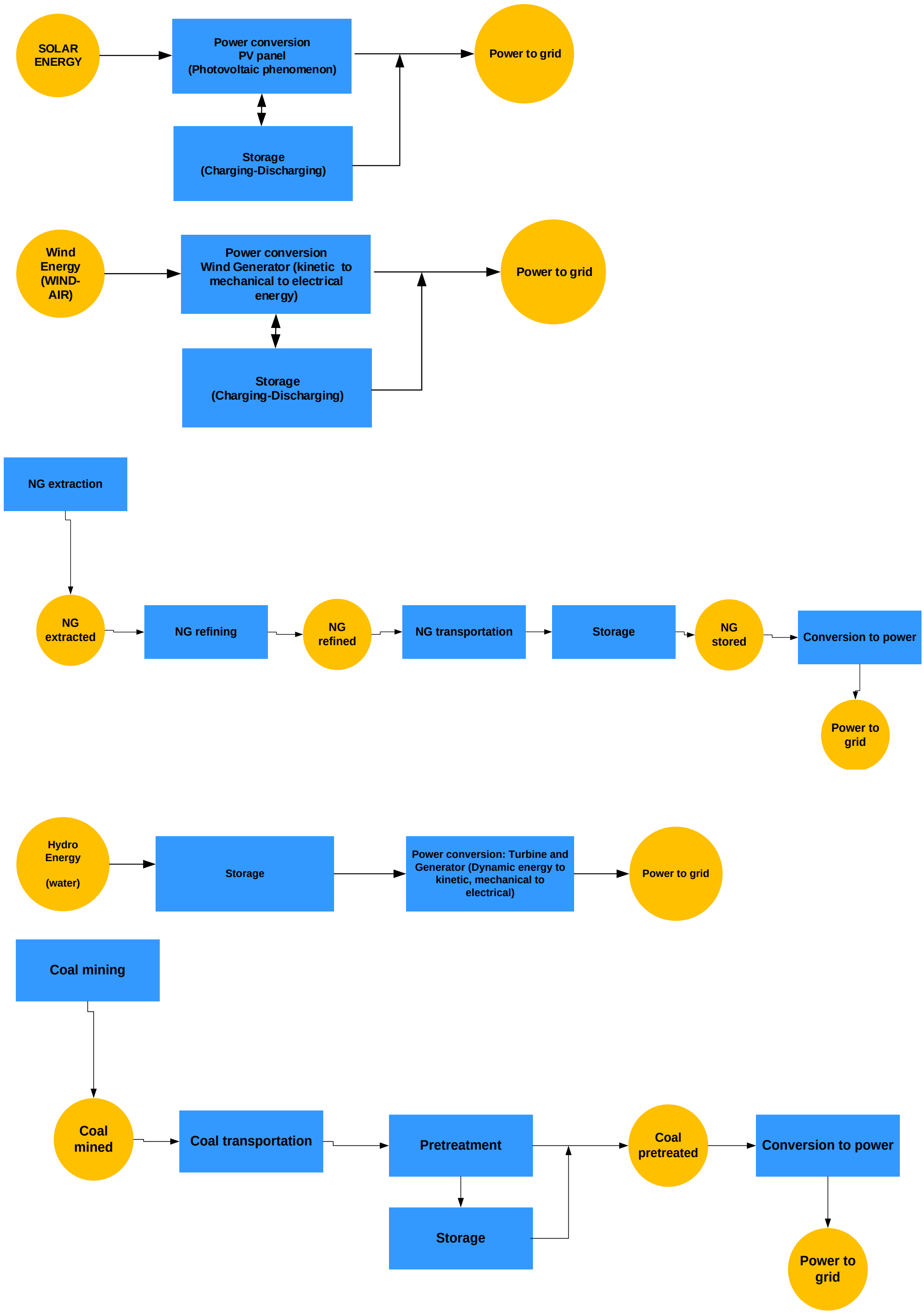


Figure 44: Top down representation of Energy and Fuel SCs

5.2 Mathematical model development of ESC

5.2.1 Model design considerations

Model design and the respective results seek to evidence the adaptability of the optimisation criterion under different set of priorities considered and provide operational data for the configuration being utilised. Results that are given in the following section gradually capture all of the different aspects previously discussed, leading to the elaboration of different scenarios for single day, month and finally annual planning decision making.

The developed mathematical model is formulated as a Multi Objective Mixed Integer Linear Programming (MO-MILP) problem, seeking to combine both discrete and continuous variables in the complex planning and operating ESCs, on top of multiple decisions (techno-economic, environmental and social) consideration. Owing that to its generic and adaptable nature and structure, the solution is sensitive to the parameters taken into consideration for the model testing. This sensitivity of the model parameters imposes the need for preciseness, as much as possible, of the selected values; otherwise the optimisation maybe rendered out of scope. The types of decisions being supported by the model include:

- Multiple stakeholders
- Multiple levels of power planning
- Strategic (investigation of the optimal utilisation of the available energy SCs and creation of new infrastructures if needed)
- Operational: for given demand and SC options, under the criteria set, the optimum fuel mix is identified under the very detailed hourly-based time-step. This case seeks also to demonstrate the role of energy storage in the security of energy supply if renewable based energy supply chains are considered.

Whist the types of problems being supported by the present modelling approach include:

- Energy fuel mix diversification (generation and capacity)
- Maximisation of security of energy supply
- Acknowledgment of the role of energy storage
- Inclusion of sustainability considerations in the energy supply schemes
- Satisfaction of multiple environmental targets and goals

- Optimal utilisation of time varying resources availability
- Simultaneous satisfaction of conflicting demands (demand prioritisation) of multiple stakeholders (i.e. remote consumers, a small city, a country, and/or a geographical area with remote /consumer characteristics) under different levels of decisions.

Model implementation is carried out under the conceptual spectrum of evidencing its applicability and adaptability to:

- Address different time scales of energy planning problems (operational and strategic)
- For different sizes of end consumers
- For different sets of energy and fuel SCs
- With or without the inclusion of the energy storage/ seeking to maximise the security of energy supply
- Evaluating primarily the existing situation (operational scenario) and proposing a more sustainable energy SC configurations (investment) with the extension of selecting at each time step the most sustainable resources of energy supply.
- Switching between different optimisation targets (assigning different weights to the different sustainability criteria)

On the input side for each specific energy planning problem investigated (Figure 45), annual time-series are used for:

- Demand (load consumption)
- solar irradiance
- wind potential (wind speed and assorted capacity factors)
- diesel consumption,

Figure 45: The proposed evaluation framework

The energy planning problem is coded using the algebraic modelling language, GAMS distribution 24.3.3 (Rosenthal, 2015), and is solved using the optimisation solver for large-scale MILP problems, CPLEX version 12.6. Typical computational time is 3.719 seconds.

All data –series utilised are imported through the appropriate GDXin utility. More specifically for the operational models, wind speed and solar irradiance data, initial values were converted into normalised power outputs by means of area specific capacity factors, whilst for diesel units the appropriate fuel conversion and load factors, were used. However, in the case of the investment model, the values of resources' capacities to be installed are the decision variables resulting from optimisation; to that end input data consist only of capacity factors of the resources examined on top of the initial dimensiosn of the energy storage system.

It must be underlined that the interconnection option is not used in the case studies following due to the lack of the appropriate official data.

5.2.2 Model nomenclature

Table 4: Parameters and variables of the proposed mathematical model

Indices	
r	Resource (wind, sun(PV), oil, LNG etc)
s	Energy storage stations
i	Interconnection option
t	Time interval for which the problem is considered (hour, day week, month)
u	Users (in terms of sectors, industry, domestic, municipalities-public buildings etc)
Sets	
R	Set of resources
S	Set of storage stations
I	Set of interconnection options
H	Time horizon or set of time intervals of the problem under consideration
U	Set of users (Demand)
Economic Parameters	
P_{EL}	Price of electricity generated (€ per kWh)
P_{EL2}	Price of electricity "being purchased from the storage stations" (€ per kWh)
P_{EL3}	Price of electricity "purchased from the interconnection option " (€ per kWh)
$INVr_r$	Investment cost of resource r (€ per kW)
$INVs_s$	Investment cost of storage station s (€ per kWh)
$INVi_i$	Investment cost of interconnection option i (€ per kW)
$INVsg_s$	Investment cost of storage generator sg (€ per kW)
$INVsp_s$	Investment cost of storage "pumping" sp (€ per kW)
MOr_r	Maintenance and operational cost of resource r (€ per kWh)
MOs_s	Maintenance and operational cost of storage station s (€ per kWh)
MOi_i	Maintenance and operational cost of interconnection option i (€ per kWh)
FCr_r	Fixed annual cost of resource r (€ per kW)
FCs_s	Fixed annual cost of storage station s (€ per kWh)
$FCsg_s$	Fixed annual cost of electricity generated at storage station s (€ per kW)
$FCsp_s$	Fixed annual cost of electricity (pumped) at storage station s (€ per kW)
FCi_i	Fixed annual cost of interconnection option i (€ per kWh)

Environmental Parameters	
$LCENVFr_r$	Life Cycle environmental footprint of resource r (kg $CO_{2\ eq}$ per kWh)
$LCENVFs_s$	Life Cycle environmental footprint of storage station s (kg $CO_{2\ eq}$ per kWh)
$LCENVFi_i$	Life Cycle environmental footprint of interconnection option i (kg $CO_{2\ eq}$ per kWh)
$LCREF$	Reference Life Cycle environmental footprint of selected ESC (in kg CO_2 eq / kWh)
$EMFr_r$	Emission factor of resource r (kg $CO_{2\ eq}$ per kWh)
LFr_r	Land footprint of power plant r (km^2 per kW)
LFs_s	Land footprint of storage station plant s (km^2 per kWh)
$Amax$	Maximum land being available for the installation of the electricity production plants of each resource r (in m^2)
$GHGmax$	Greenhouse Gas emissions reduction coefficient (%)
Social Parameters	
$EMPLr_r$	Employment yield of resource r (€ per kWh)
$EMPLs_s$	Employment yield of storage station s (€ per kWh)
$EMPLi_i$	Employment yield of interconnection option i (€ per kWh)
$SECr_r$	Energy security index for each ESC (0=for RES based plants -1=for imported diesel and natural gas)
$SECs_s$	Energy security index for storage station s (1=for energy storage stations)
$SECi_i$	Energy security index for the interconnection option (-1=for interconnection)
PCO_2	Commercialisation price of CO_2 (€/kWh)
PEX	Exchange losses from imported energy (and resources) (€/kWh)

Technical Parameters	
nr_r	Efficiency of electricity generation plant r
nch	Pumping - generation rate of charging / discharging
np	Storage “pumping” station charging efficiency coefficient
ng	Storage generator discharging efficiency coefficient
$nl\,max$	Maximum energy storage level coefficient
$nl\,min$	Minimum energy storage level coefficient
$ESS\,min_{t,s}$	Minimum operational capacity of storage station s (kWh)
$ESS\,max_{t,s}$	Maximum operational capacity of storage station s (kWh)
$CFr_{t,r}$	Capacity Factor of electricity production plant r, at time step t
$CFs_{t,s}$	Capacity Factor of storage station s, at time step t
$CFi_{t,i}$	Capacity Factor of interconnection option i, at time step t
$CAPrmax_{t,r}$	Maximum capacity of electricity production plant r, at time step t (MW)
$CAPrmin_{t,r}$	Minimum capacity of electricity production plant r, at time step t (MW)
$INT\,max_{t,i}$	Maximum capacity of interconnection option i, at time step t (MW)

Binary variables	
$Br_{t,r}$	Binary variable considering the operation (=1) or not (=0) of electricity production plant r, at time step t
Continuous variables	
$EG_{t,r}$	Energy (electricity) generation from resource r, at time-step t (in kWh)
$ESg_{t,s}$	Energy (electricity) being generated by storage station s at time-step t (in kWh)
$ESs_{t,s}$	Energy (electricity) being stored at storage station s, at time-step t (in kWh)
$ESl_{t,s}$	Energy storage level
$EIN_{t,i}$	Energy (electricity) imported/exported (from the interconnection i) at time-step t (in kW)
Pr_r	Nominal capacity of electricity production plant r (in kW)
Ps_s	Nominal capacity of storage station s (in kWh)
Psg_s	Nominal capacity of storage generation / discharging station s (in kW)
Psp_s	Nominal capacity of storage pumping / charging stations (in kW)
Pi_i	Nominal capacity of interconnection i (in kW)

5.2.3 Objective function

The optimisation criterion (Eq. 8) seeks to express the optimal energy supply set of options by maximising the total benefit of the ESC. To that end, three distinctive Values (Economic, Environmental and Social) are considered, assessing diverse performance criteria of different time-scales, levels of decisions as well as various scales of economies (micro and macro).

$$Max = \left\{ a_1 \times ECONV + a_2 \times ENVV + a_3 \times SOCV \right\} \tag{8}$$

where, a_1, a_2, a_3, appropriate weighted ($\alpha_1=\alpha_2=\alpha_3=0.333$) (equally considered), normalisation factors of the different sustainability dimensions, as they are of equivalent magnitude as well.

5.2.3.1 Economic Value

The economic value $ECONV$ considers Incomes from electricity being generated from resources ($EG_{t,r}$), energy storage ($ESg_{t,s}$) and interconnection ($EIN_{t,i}$) that is being sold to the Network Operator minus Total Costs (TC) resulting from electricity generation and acquisition (Investment, Maintenance and Operational Costs, Fixed Annual Cost, Electricity Purchase Cost from the storage stations and the interconnection) (€).

$ECONV =$ (9) + (10) + (11) + (12) + (13)

Revenues from electricity selling

$$\sum_t \sum_r EG_{t,r} \cdot P_{EL} + \sum_t \sum_s ESg_{t,s} \cdot P_{EL} + \sum_t \sum_i EIN_{t,i} \cdot P_{EL} \tag{9}$$

Acquisition costs

$$-\sum_t \sum_i EIN_{t,i} \cdot P_{EL3} - \sum_t \sum_s ESs_{t,s} \cdot P_{EL2} \tag{10}$$

Investment costs

$$-\sum_r INVr_r \cdot Pr_r - \sum_s INVs_s \cdot Ps_s - \sum_s INVsg_s \cdot Psg_s - \sum_s INVsp_s \cdot Psp_s - \sum_i INVi_i \cdot Pi_i \tag{11}$$

Fixed Annual costs

$$-\sum_r FCr_r \times Pr_r - \sum_s FCs_s \cdot Ps_s - \sum_s FCsg_s \cdot Psg_s - \sum_s FCsp_s \cdot Psp_s - \sum_i FCi_i \cdot Pi_i \tag{12}$$

Maintenance and Operational Costs

$$-\sum_t \sum_r EG_{t,r} \cdot MOr_r - \sum_t \sum_s ESg_{t,s} \cdot MOs_s - \sum_t \sum_s ESs_{t,s} \cdot MOs_s - \sum_t \sum_i EIN_{t,i} \cdot MOi_i \tag{13}$$

5.2.3.2 Environmental Value

The environmental value – $ENVV$ reflects the environmental positive impact of the ESC configuration in Life Cycle Analysis. Each ESC's Life Cycle Environmental Footprint is compared to an environmental friendly ESC for which a Reference Life Cycle Environmental Footprint is selected ($LCREF$). This is described for the set of resources, storage stations and interconnection options as follows:

$$
\begin{aligned}
& ENVV = \\
& \sum_t \sum_r \left[EG_{t,r} \cdot \left(LCREF - LCRENVFr_r \right) \cdot PCO_2 \right] \\
& + \sum_t \sum_s \left[ESg_{t,s} \cdot \left(LCREF - LCRENVFs_s \right) \cdot PCO_2 \right] \\
& + \sum_t \sum_i \left[EIN_{t,i} \cdot \left(LCREF - LCRENVFi_i \right) \cdot PCO_2 \right]
\end{aligned}
\tag{14}
$$

where PCO_2 is the current price of CO_2 (€/kWh), $LCREF$ the reference ESC environmental value and $LCENVFr_r$, $LCENVFs_s$, $LCENVFi_i$ is the environmental footprint (in LCA terms) of each ESC of resources, storage stations and interconnections respectively.

5.2.3.3 Social value

Social value – $SOCV$ of the ESC considers micro and macro – economic benefits from the implementation and operation of the different ESC configurations (€):

$$SOCV = MiSOCV + MaSOCV \tag{15}$$

Micro-social benefits are calculated on the basis of the employment yield offered from each ESC:

$$
\begin{aligned}
& MiSOCV = \\
& \sum_t \sum_r \left(EMPLr_r \cdot EGr_{t,r} \right) + \sum_t \sum_s \left(EMPLs_s \cdot ESg_{t,s} \right) + \sum_t \sum_i \left(EMPLi_i \cdot EIN_{t,i} \right)
\end{aligned}
\tag{16}
$$

where $EMPLr_r$, $EMPLs_s$ $EMPLi_i$ is the employment yield (€/ kWh) per annum for each ESC in the area/field under consideration.

Macro-economic benefits function seeks to introduce the issue of energy security and the negative impacts of exchange losses by the import of either resources and/or final energy-electricity. This is described by equation 17:

$$\begin{aligned} & MaSOCV = \\ & \sum_t \sum_r \left(SECr_r \cdot PEX \cdot EGr_{t,r} \right) + \sum_t \sum_s \left(SECs_s \cdot PEX \cdot ESg_{t,s} \right) \\ & + \sum_t \sum_i \left(SECi_i \cdot PEX \cdot EIN_{t,i} \right) \end{aligned} \tag{17}$$

where SEC is the Energy Security index of each ESC which is dependent on the type (location dependent- inland or imported and based on the type of feedstock –resource used for electricity generation - $SECr_r = 0$, for RES based plants $SECr_r = -1$, for imported diesel and natural gas, $SECs_s = 1$, for energy storage, $SECi_i = -1$ for the interconnection) of electricity being generated and PEX (€/kWh) is the equivalent exchange losses in Euros spent in each case for electricity generation from any type of imported energy (and resources).

5.2.3.4 Model constraints and resources balances

Model constraints and resources' balances reflect the technical and physical limitations and operational characteristics of the system. So on the side of electricity generation we have:

- **Electricity generation equations**

$$EG_{t,r} = Pr_r \cdot CFr_{t,r}, \quad \forall t, \forall r \tag{18}$$

$$EIN_{t,i} = Pi_i \cdot CFi_{t,i}, \quad \forall t, \forall i \tag{19}$$

where Pr_r, Pi_i is the nominal capacity of resource plant *r* and of the interconnection option *i* and $CFr_{t,r}, CFi_{t,i}$ is the time-varying Capacity Factor reflecting the operation rate of the electricity generation plant *r* and interconnection option *i* accordingly.

- **Electricity production plants capacity limitations (minimum and maximum) for each supply resource**

$$CAPr\,max_{t,r} \geq EG_{t,r} \cdot Br_{t,r}\,, \quad \forall t, \forall r \tag{20}$$

$$CAPr\,min_{t,r} \leq EG_{t,r} \cdot Br_{t,r}\,, \quad \forall t, \forall r \tag{21}$$

where $Br_{t,r}$ is a binary variable considering the operation (=1) or not (=0) of electricity production plants r in each time step t.

- **Limitation in selection of resources r to one**

$$\sum_{r} Br_{t,r} = 1,\ \forall t \tag{22}$$

with this constrained in applicable in the binary version of the model.

- **Capacity limitations of the interconnection supply resources**

$$INT\,max_{t,i} \geq IPi_{i}\ , \forall t, \forall i \tag{23}$$

where Pi_i is the Nominal capacity of interconnection *i* and $INT\,max_{t,i}$ is the maximum capacity of interconnection option i.

- **Storage stations capacity limitations in generation and pumping**

Energy generated or pumped is a function of the generator or pumping capacity multiplied by the relevant efficiency factor np or ng (in our case since a typical battery storage system is examined pumping capacity Psp_s is considered to be equal to generating capacity Psg_s. The same applies for the efficiency factors.

$$ESg_{t,s} \leq ng \cdot Psg_{s}\ , \forall t, \forall s \tag{24}$$

$$ESs_{t,s} \leq np \cdot Psp_{s}\ , \forall t, \forall s \tag{25}$$

where $ESg_{t,s}$ is the electricity being generated by storage station at time-step t (in kWh), and $ESs_{t,s}$ is the electricity being stored at storage station s, at time-step t (in kWh).

- **Energy storage level constraints**

Energy storage level must float between an upper and a lower value ($ESS\,max$ and $ESS\,min$)

$$ESl_{t,s} \leq nl\,max \cdot Ps_{s}\,(ESS\,max)\ , \forall t, \forall s \tag{26}$$

$$ESl_{t,s} \leq nl\,min \cdot Ps_{s}\,(ESS\,min)\ , \forall t, \forall s \tag{27}$$

- **Storage balance-rate of charge of the storage stations**

The energy storage level at time-step t, is the energy being stored at a previous time-step plus the energy stored being supplied to the system minus the energy being generated (needed).

$$ESl_{t,s} = ESl_{t-1,s} - \left(\frac{1}{ng} \cdot ESg_{t,s}\right) + np \cdot ESs_{t,s}, \ \forall t, \forall s \tag{28}$$

$$Psg_s = nch \cdot Ps_s \left(ESS\,max\right), \forall t, \forall s \tag{29}$$

$$Psp_s = nch \cdot Ps_s \left(ESS\,max\right), \forall t, \forall s \tag{30}$$

where Psg_s the nominal capacity of storage generation / discharging station s (in kW), Ps_s the nominal capacity of storage station s (in kWh), nch the pumping - generation rate of charging / discharging.

- **Satisfaction of the demand**

Power generated must fulfil the demand alongside the utilisation of the energy storage.

$$\sum_u v_{t,u} = \sum_r EGr_{t,r} + \sum_s ESg_{t,s} - \sum_s ESs_{t,s} + \sum_i EIN_{t,i}, \ \forall t \tag{31}$$

- **Land availability limitations of each supply resource and storage station**

In the case of new plants' installation, land limitations should be considered. Each plant including the energy storage option has a specific land footprint. The solution of interconnection is considered to have zero land footprint. The land limitation is described by the subsequent equation:

$$\sum_r Pr_r \cdot LFr_r + \sum_s Ps_s \cdot LFs_s \leq A\,max \tag{32}$$

- **Environmental impacts (in kg CO_{2eq}) limitations:**

In order to apply an environmental limitation to the amount of CO_2 equivalent emissions that are being produced from fossil based electricity generation resources and relevant technologies, a collective 20% reduction goal is set, as a precursor of the European Union's ambitious target for reducing *greenhouse gas emissions by* 2020. To that end, an upper bound - $GHG\,max = 0.8$ is imposed on the total amount of electricity generated.

This target is given by the following equation:

$$\sum_r EGr_{t,r} \cdot EMFr_r \leq GHGmax \cdot \sum_u v_{t,u} \text{ , } \forall t \tag{33}$$

where EMF_r is the emission factor in kg CO_2 per kWh produced of the fossil based electricity generation technologies. Storage stations, renewable based plants as well as the interconnection option are considered to have zero emission factors.

5.3 RTN representation for ESC modelling

The RTN representation adopted for the specific energy planning problem is illustrated in Figure 46. So, on the supply side of resources (R_R) there are:

- energy (wind, PV (solar to power)), (R_R),
- fuel based resources (diesel, coal, natural gas), (R_R),
- interconnection and (R_I),
- energy stored (R_S) which can be a primary resource in the case of hydropower or an intermediate resource in the case of electricity being stored,
- finally, one may also add in the set of resources the Power (R_P) supplied to the grid.

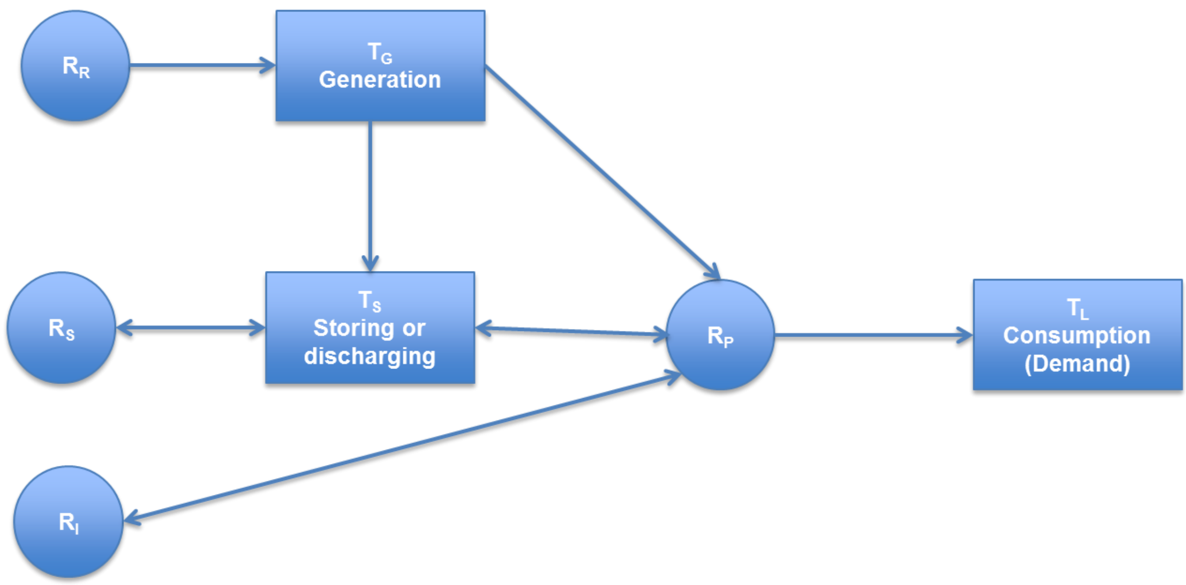


Figure 46: The adapted RTN representation for the ESC modelling

On the side of tasks (processes) being carried out, there is the conversion to power (T_G) (from each one of the resources considered except from the interconnection T_I which directly supplies electrical energy) and storage operation-(T_S), which includes both the charging and discharging function. At the final stage we have the consumption task (T_P) –Load/Demand, which is time-varying and which is a critical input in the model for the optimisation.

The dimension and description of resources and their connection to tasks is illustrated in Table 5. For example, for the set of Resources R (which can be both energy and fuels) the resulting variable which is the electricity generated $EG_{t,r}$ is a function of an appropriately selected conversion factor multiplied by the capacity Pr_r of each electricity generation plant $(EG_{t,r} = Pr_r \cdot CFr_{t,r})$.

For each combination of resources, specific tasks are used to form an ESC with operation designated to meet the final power demand. For all the sets of indices (resources, storage, interconnection and users) there exist appropriate assigned technical, economic, environmental and social parameters. The optimum ESC configuration is determined through the optimisation of the total value of the ESC (benefits – total costs) subject to the constraint that power supply meets the final demand under techno-economic, environmental and social implications consideration. Applicability of the proposed ESC configuration and the respective equations of power generation and consumption will be evidenced in Chapter 6, with the case studies analysis for the specific energy planning problem.

Table 5: ESC: Resources-to-Task modelling introduction

Resource	Description	Variable (Unit)	Capacity Factors (Conversion –to- power factor)	Task Description	Notes
R_R	Resources and Fuels (either Renewable or Fossil –based)	$EG_{t,r}$ (kWh)	$CFr_{t,r}$ Time-varying capacity factor with limits: $0 \le CFr_{t,r} \le 1$	$T_G: \ EG_{t,r} = Pr_r \cdot CFr_{t,r}$ Limited to: $CA\,Pr\,min_{t,r} \le EG_{t,r} \cdot Br_{t,r}$ $CA\,Pr\,max_{t,r} \ge EG_{t,r} \cdot Br_{t,r}$	On the side of resources either we have given values of wind speed, solar irradiation and fuel oil consumption (being appropriately converted to power outputs in each time-steo) as in the case of operational model or in the case of investment model, given the capacity factors for the set of resources, the assorted capacities are resulted from the optimisation.
R_S	Stored energy	$ESg_{t,s}$ $ESs_{t,s}$ $ESl_{t,s}$ (kWh)	$CFs_{t,s}$ Time-varying capacity factor which floats between the minimum and maximum operational capacity of storage station s: $ESS\,min \le CFs_{t,s} \le ESS\,max$	T_S $ESl_{t,s} = ESl_{t-1,s} - \left(\frac{1}{ng} \cdot ESg_{t,s}\right) + np \cdot ESs_{t,s}$ Considering the operational characteristics of the storage system: $ESg_{t,s} \le ng \cdot Psg_s$ $ESs_{t,s} \le np \cdot Psp_s$ $ESl_{t,s} \le nl\,max \cdot Ps_s\,(ESS\,max)$ $ESl_{t,s} \le nl\,min \cdot Ps_s\,(ESS\,min)$	Storage system operation could be used equally in the case of a water reservoir, or a simple battery charging function.
R_I	Imported or exported power	$EIN_{t,i}$ (kWh)	$CFi_{t,i}$ Time-varying variable factor with limits: $0 \le CFi_{t,i} \le 1$	T_I $EIN_{t,i} = Pi_i \cdot CFi_{t,i}$ Limited to: $INT\,max_{t,i} \ge IPi_i$	In each time step interconnection is being subjected to technical limitations concerning its capacity.
R_P	Grid power	kW	Sum of all outputs and inputs of linked tasks Constrained to = 0	T_P $\sum_u v_{t,u} = \sum_r EGr_{t,r} + \sum_s ESg_{t,s} - \sum_s ESs_{t,s} + \sum_i EIN$	Power supplied to end customers in the grid examined is set to consider all the available resources on top of the energy storage operation.

CHAPTER 6: METHODOLOGY VALIDATION AND IMPLEMENTATION

In this chapter the proposed methodology for the evaluation of energy and fuel SCs is tested and validated through exemplar case studies. The case studies under consideration seek to representatively assess the energy planning problem of an isolated community in terms of fully meeting the electricity demand in the most sustainable way. To that end, different time scales of the problem as well different sizes of end consumers are examined. Simulation results from the latest developed model as well as from published research work are presented as well.

6.1 Description of the energy planning problem: problem statement

The energy planning problem is of primary importance during the last years mainly due to the pressing issues of security of energy supply, of cost minimisation, of environmental restrictions and regulations, and more recently of social considerations requiring equal access for everybody to energy infrastructures. At the same time technology supports many more options and alternative solutions in the design of the ESCs with the introduction of alternative and RES-based energy sources.

Concerning the situation in Greece, the national fuel mix maybe characterised as fossil-based as it is strongly dependent on locally extracted lignite (Kaldellis et al., 2005, Kaldellis et al., 2009b) which is the primary energy source for electricity production, accounting for roughly 45% of total generation (end of 2013). Imported natural gas-fired and large hydro power plants provide approximately 24 % and 12% of the gross electricity fuel mix respectively. RES-based stations (hydro-power, wind, solar/PV and biomass) contribute at a share of 16% (hydro-power contributed ~7%, wind energy ~6.5%, solar photovoltaic ~2% and biomass ~0.5%), presenting a relatively significant increase of 5% during the last recorded year (2012-2013) (owing that to the increased installed capacity of PVs). Finally imports are set at 3% (Independent Power Transmission Operator (IPTO, 2015).

At the same time, the Greek Electricity Generation System (EGS) presents a particular topography since it is divided in two discrete sub-sectors, i.e. (a) the interconnected mainland electricity production network and (b) the corresponding non-interconnected Aegean Archipelago islands (mainly supported by thermal power units -Autonomous and

Local Power Stations, all operating on the basis of imported amounts of diesel and heavy oil).

Greece is a very interesting case study for electricity generation and the respective electricity market as it presents the following characteristics:

- It relies heavily on indigenous low-quality lignite that gives rise to CO_2 emissions concerns.
- The non-interconnected system experiences extreme electricity production costs that may even exceed 1€/kWh for the smaller-scale island regions as a result of the necessary oil imports.
- Greek end consumers on the other hand, both on the mainland and islands, are used to enjoying one of the lowest retail electricity prices in Europe, owing that to state subsidisations.
- There is a vast RES potential in the Greek territory and especially in island regions that has only been partly exploited.
- Non-interconnected islands are also facing energy supply security issues that encourage the investigation of alternative, carbon lock-out practices. In fact, island regions are considered to be ideal test-beds for the examination of novel energy schemes introducing smart-grids, RES, distributed generation, energy storage and demand side management practices. In the case of Aegean Greek islands, to their majority, they are dealing with significant seasonal variation of electricity demand due to the increased tourism during the summer months. This variation, has resulted several black-outs proving the existing electricity supply infrastructure insufficient.

So the investigation and possibly the resolution of the Greek energy planning problem in the non-interconnected islands renders a very interesting research area especially when introducing in the decision-making process, on top of techno-economic criteria- sustainability dimensions like environmental limitations and air quality standards as well as social issues like the energy security maximisation and the maximisation of the local / community's welfare.

To this end, the proposed evaluation framework for alternative energy and fuel SCs will be tested with reference to the Greek island communities, for a set of different sized energy consumers, for multiple time steps with remote /site characteristics, and with or without the energy storage option/inclusion. The designated system and its conceptualisation is elaborated under the spectrum of energy security maximisation: i.e. when there is energy surplus, the excess of energy is stored and returned to the supply system whenever there is deficit (Figure 47). Of course the charging and discharging of storage is not only subject to, and controlled by, technical and economic criteria but also by environmental limitations and air quality standards on top of the social aspects and criteria.

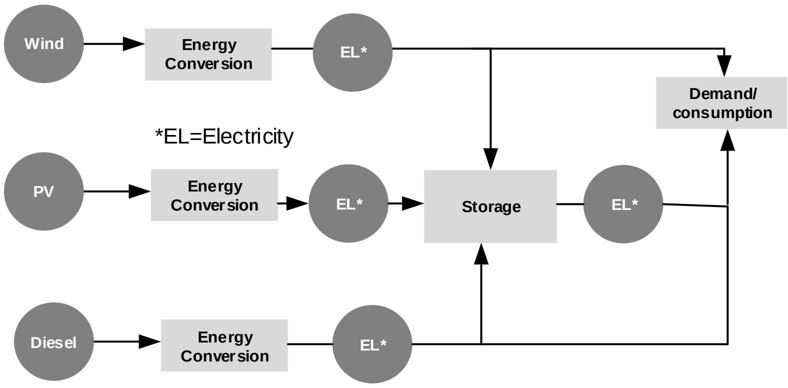


Figure 47: RTN representation of energy planning problem

6.2 Input data

The scenarios considered for model evaluation are designated for different sizes of island for operational and investment decision-making. So we have:

- Single island cases (assessed for different time-steps) – (see APPENDIX C)
- Set of islands: operational optimisation cases
    - Optimisation of existing situation
    - Optimisation results with inclusion of energy storage
    - Optimisation results with inclusion of binary variables
- Set of islands: large-scale investment optimisation

In order to meet the aim of the present work which is the maximisation of the total value of the ESC in terms of sustainability three different sets of costs parameters are considered: techno-economic, environmental and social. Each one is quantified on the basis of the functional unit of the system i.e. €/kWh or €/kW. The selected parameters seek to reflect in the most optimal way the different implications of energy and fuel SCs, to be represented by the three different objective function in the optimisation criterion. To that end the following sets of cost parameters are considered:

Techno-Economic parameters

- Electricity selling price to the Distribution Network Operator

- Maintenance and operational variable cost (of new and existing plants)[3]
- Resources capital cost (for new plants) [4]
- Annual fixed cost (associated with resources capital cost)[5]
- Electricity purchase cost from the energy storage station

Environmental

- Current commercialisation price of CO_2

Social

- Exchange losses from imported energy
- Employment yield from each ESC

Values selected for model testing, include reference works carried out in Greece mapping out the special characteristics of the Greek electricity system are used. Some selected values from the Greek related bibliography are illustrated in Tables 21 and 22 in Appendix B, whilst the specific values applied in the following case studies are illustrated in Table 6.

More specifically concerning the case of the investment costs of the plants under evaluation, annualised values under a respective lifetime for each one (approximately 15 years) is considered. Typical values for maintenance and operational costs for the plants are estimated and in the case of diesel power production plants the price of consumed fuel is also included[3]. Fixed costs are also being calculated as a function of the capitals costs. In respect to environmental values the current commercialisation price of CO_2 is used in order to introduce a reasonable market price regarding greenhouse gas emissions expressed as in €/kWh, considering typical emission rates for fossil power plants in Greece.

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[3] Maintenance and operational cost are only considered for diesel electricity generation plants and include the cost of fuel consumption and are calculated with respect to the following formula: For a typical diesel generator size approximately of 1000kW, fuel consumption at 3/4 load is 198 lt/h heating diesel at an average fuel price 0.8€/lt

[4] Investment cost for each of the resource/ plant is considered as follows: wind: 1100(€/kW), PV: 1200 (€/kW), diesel: 850(€/kW), storage 650(€/kWh). For the values assigned, an annualised price for time –period (life plant cycle) of 15 years is used.

[5] Annual Fixed Cost is calculated as a percentage of the investment cost:
Wind=1-4% of the investment cost - value selected 1%
PV=1% of the investment cost - value selected 1%
Diesel=4-8% of the investment cost - value selected 4%
Storage=2-5% of the investment cost - value selected 2%

In addition, on the side of social parameters, we have the employment rate consideration expressed as €/kWh produced, and the exchange losses (PEX) from imported energy. This is calculated as a function of the cost of imported oil. With known values for the price of an imported barrel of oil for Greece (Figure 48), this value is converted to kWh of produced power by the following formula: 1 barrel of oil equivalent (boe) contains approximately 0.146 toe, 1 toe = 11.63 megawatt hours, so 1 barrel equals to ~1.7 MWh and from that data mobilised from (costs year 2012) approximately 100$. So 1 kWh of imported oil converts to a power cost to Greece of approximately 0.078 €.

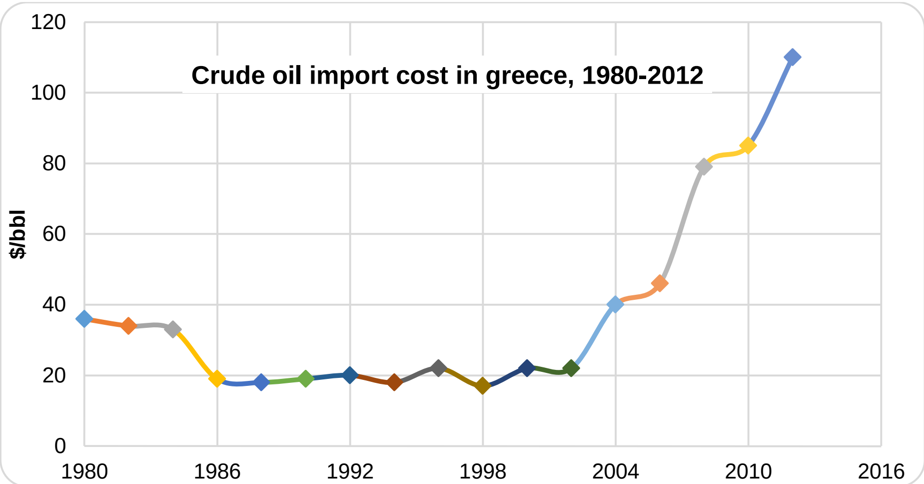

Figure 48: Crude oil import cost in Greece, 1980-2012 (Danchev & Maniatis, 2014)

Table 6: Parameters selected for model validation (sets of islands-operational model and case of storage consideration)

Weighting factors		$a_1 = 0.333$	$a_2 = 0.333$	$a_3 = 0.333$	
Economic Parameters	**All/**	**Wind**	**PV**	**Diesel**	**Storage**
$INVr_r$ (€/kW)	●	**73**	**80**	**57**	●
$INVs_s$ (€/kWh)	●	●	●	●	**43**
$INVsg_s$ (€/kW)	●	●	●	●	0
$INVsp_s$ (€/kW)	●	●	●	●	0
P_{EL} (€/kWh)	0.14	●	●	●	●
P_{EL2} (€/kWh)	●	●	●	●	0.14
MOr_r (€/kWh)	●	0.16	0.16	0.16	
MOs_s (€/kWh)	●	●	●	●	0.00
Environmental	**All/**	**Wind**	**PV**	**Diesel**	**Storage**
$LCENVFr_r$ (kg $CO_{2\,eq}$ / kWh)	●	0.065	0.150	0.770	
$LCENVFs_s$ (kg $CO_{2\,eq}$ / kWh)	●	●	●	●	0.275
$LCREF$ (kg $CO_{2\,eq}$ / kWh)	0.065	●	●	●	●
$EMFr_r$ (kg $CO_{2\,eq}$ / kWh)	●	0	0	0.8	
LFr_r (km^2 / kW)	●	0.0079	0.0012	0.00000064	●
LFs_s (km^2 / kWh)	●	●	●	●	0.00000002
$Amax$ (km^2)	1000	●	●	●	●
Social Parameters	**All/**	**Wind**	**PV**	**Diesel**	**Storage**
$EMPLr_r$ (€/kWh)	●	0.00099	0.00118	0.00148	●
$EMPLs_s$ (€/kWh)	●	●	●	●	0.000099
$SECr_r$	●	0	0	-1	●
$SECs_s$	●	●	●	●	1
PCO_2 (€ /kg)	0.015	●	●	●	●
PEX (€/kWh)	0.078	●	●	●	●
np	0.90	●	●	●	●
ng	0.90	●	●	●	●
nr_r	●	1	1	1	●
nch	0.25	●	●	●	●

Technical Constraints	All/	Wind	PV	Diesel	Storage
$ESS\ min_{t,s}$ (kWh)	●	●	●	●	0
$ESS\ max_{t,s}$ (kWh)	●	●	●	●	150,000
$CFr_{t,r}$	In this case is considered equal to power out of the considered resource (in kW) in an hourly based time step				
$CFs_{t,s}$	In this case is considered equal to power out of the considered resource (in kWh) in an hourly based time step				
$CAPrmax_{t,r}$	Maximum capacity of each electricity production plant r, at time step t (MW)				
$CAPrmin_{t,r}$	Minimum capacity of each electricity production plant r, at time step t (MW)				

6.3 Case study: Set of islands, operational optimisation

In this set of modelling results, an integrated assessment of an electricity supply problem for a set of interconnected islands in Dodecanese Complex, is examined as follows:

a) Operational level – evaluating the existing situation – the current electricity fuel supply mix

b) Operational level-modifying the energy fuel mix with the introduction of the energy storage as a security back-up in the system

c) Operational level –by making an hourly-based assessment with the utilisation of a binary variable of the most sustainable –under the criteria set-source of energy supply

The optimiser selected for case studies implementation is GAMS 24.3.3 and the solver CPLEX version 12.6. In Appendix D, the specific developed GAMS codes can be found. All optimisation resulted are quoted on the basis of:

- Total energy Output (kWh) of each resource utilised (wind, PV, diesel and storage)
- Overall value (€) of the ESC configuration (as well as of the respective economic, environmental and social values)
- Resources (wind, PV and diesel) capacity annual distribution

6.3.1 Optimisation of existing situation

Model implementation is carried out for a typical load demand profile in a set of Greek interconnected islands in Dodecanese complex: Kos, Kalymnos, Leros, Nisyros, Tilos, Leipsoi, Telendos, Pserimos (Figure 49). Data retrieved from Hedno, for the year 2013, include hourly based energy fuel mix utilisation, as well as solar and wind energy potential. The current situation is assessed under the demand and energy supply existing characteristics (fuel mix and contribution) under the particularly of interconnection supply option (Figure 50). For the two operational scenarios following (evaluation of existing situations, and operational optimisation with the inclusion of the energy storage solution), Greenhouse gases emissions' reduction goal $GHGmax$, is considered not applicable. Model statistics for this set of scenarios include 16 blocks of equations, 122,646 single equations, 11 blocks of variables, 61,326 single variables, generation time 3.719 seconds, and memory usage 27 Mb. The solver used was CPLEX version 12.6.

Figure 49: The set of Greek interconnected islands

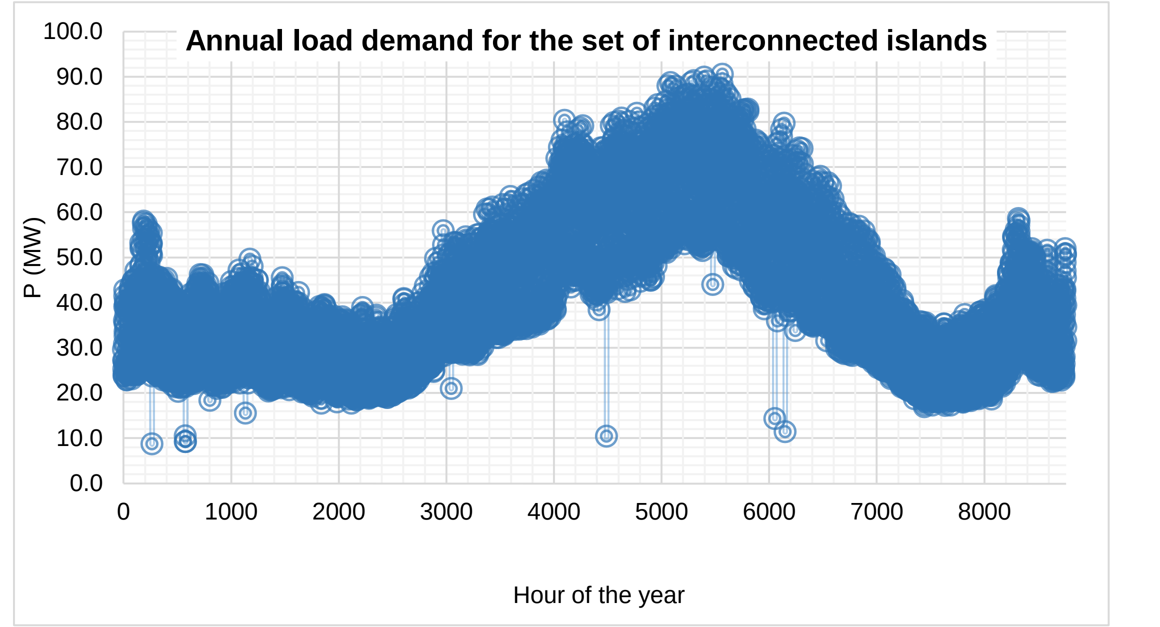

Figure 50: Annual load demand for the set of interconnected islands for 2013

As one may see from the current based energy fuel mix utilisation (Figure 51) is heavily based on diesel oil whilst very important is wind energy contribution. Wind energy harvesting presents a very good wind capacity factor approximately at 22% (with PV/ solar energy at ~17.5%). In terms of capacity the diesel maximum power output is 86,100 kW whilst for wind and 15,200 kW and PV 8,467 kW accordingly.

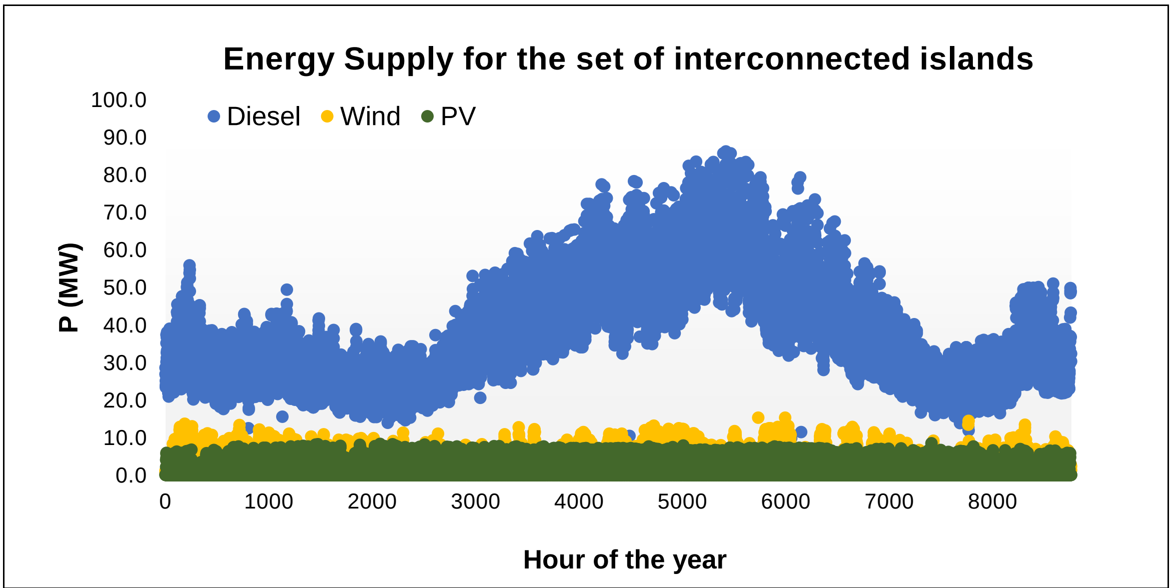

Figure 51: Current energy supply under the existing set of resources

The current situation is assessed using the provided demand and the existing energy supply characteristics (fuel mix and contribution). For providing a basis for evaluation of the existing energy supply, annual energy production output in total as well as from each resources individually, is illustrated in Table 7 and in Figures 52-54. As one may notice from these illustrations (Figures 52-54) although diesel and PV stations present a good rate of utilisation in an annual basis, wind electricity generation station seems that it is not optimally sized, since its maximum capacity is utilised only a few hours per year. This will be further exploited with the energy storage scenario considering harvesting wind energy rejections.

Table 7: Annual energy production from the set of resources

Total energy Output (kWh)	Diesel (kWh)	Wind (kWh)	PV (kWh)
362,614,745	319,060,821	29,830,080	13,723,844

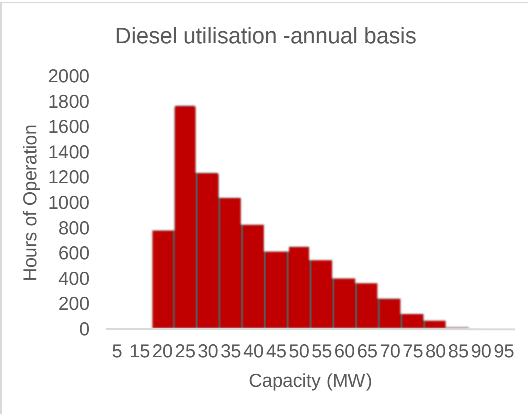

Figure 52: Diesel capacity annual distribution

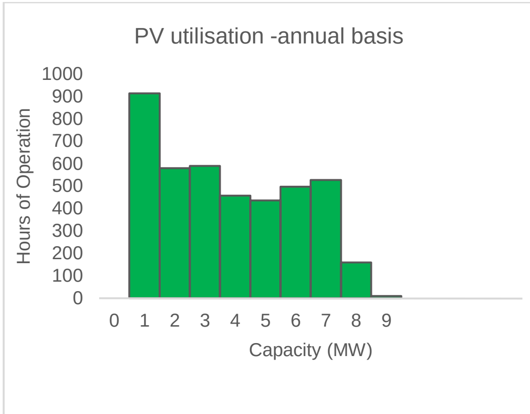

Figure 53:PV capacity annual distribution

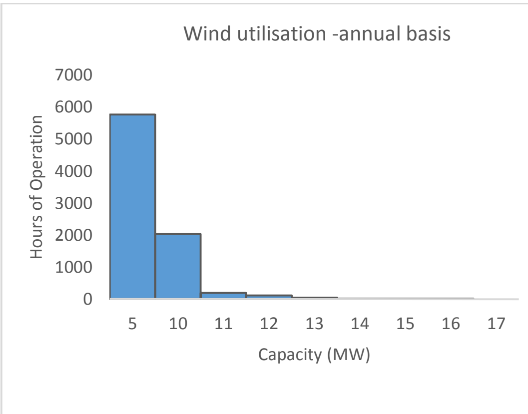

Figure 54: Wind capacity annual distribution

Optimisation results for this preliminary scenario prove the unsustainable operation of the existing ESC configuration, presenting a negative overall value (Table 8) but also a very negative environmental and social value: this is due to extended presence of diesel oil, which results a damaging environmental implication as a fossil based resource and a macro-social undesirable implication as well as it is totally imported. These values will be served as reference ones for the scenarios/ assessment - improvement that will be investigated.

Table 8: Overall and distinctive values from evaluation of the existing situation

Overall value (€)	Economic (€)	Environmental (€)	Social (€)
-9,338,666	-283,667	-3,391,566	-24,368,808

6.3.2 Operational model with the inclusion of energy storage

In this scenario the inclusion of the energy storage option for wind energy rejections' harvesting is considered. The goal is the security maximisation of the electricity supplied. For that reason energy storage station maximum capacity is accounting for a 3 hours autonomy (i.e. $ESS\,min_{t,s}$ = 0 kWh, and $ESS\,max_{t,s}$ =150,000 kWh), seeking to respond to the maximum load demand requested throughout the year. Results from this modified operational scenario are illustrated in Tables 9,10. Operational characteristics of the new ESC configuration are shown in Figures 55-62.

Table 9: Overall and distinctive values for scenario with energy storage inclusion

Overall value (€)	Economic (€)	Environmental (€)	Social (€)
-6,655,773	91,551	-3,679,958	-16,398,899

Table 10: Annual energy production from the set of resources

Diesel (kWh)	Wind (kWh)	PV (kWh)	Storage (kWh)
316,715,709	55,497,280	13,723,844	99,425,741

Modelling implementation, under the pre-set values for the specific case study evidences a better system overall value (-6,655,773€) if compared to the existing situation (-9,338,666€). This significant improvement is an output of the amelioration of all the distinctive values of the optimisation problem and especially the social value, resulting from energy security which is a result of the energy storage introduction on the side of energy security maximisation.

So, under that goal, of having a backup system ready to respond to a case of an outage, the storage station is kept full at the end of the day (almost all of the time) while within the day exchanges energy with the network operator (changing and discharging function), Figure 62. Another very important output of the specific ESC configuration is that the diesel contribution is slignhtly reduced and replaced by wind energy, being rejected up till now (Table 10). In addition, the wind energy operation presents a smoother profile, as there are no technical limitations for energy harvesting with the introduction of energy storage.

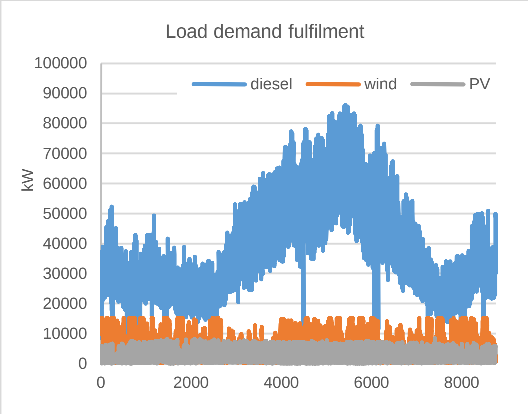

Figure 55: Load demand fullfilment

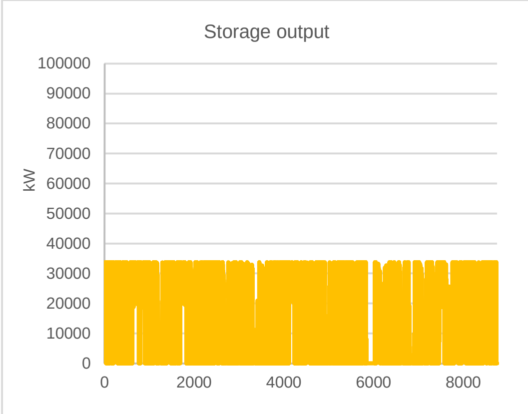

Figure 56: Storage output

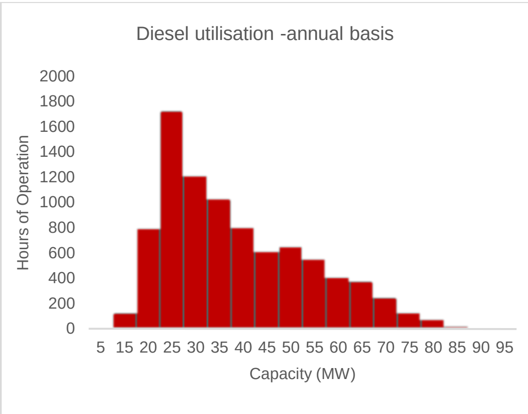

Figure 57: Diesel capacity annual distribution

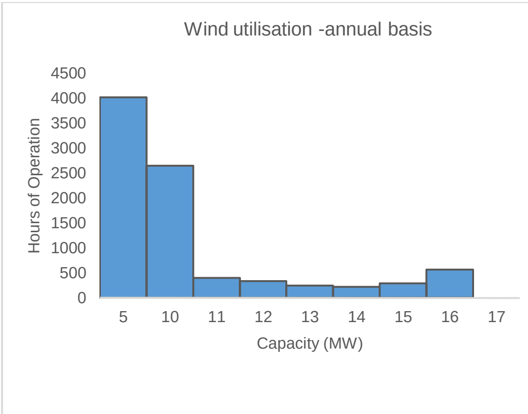

Figure 58: Wind capacity annual distribution

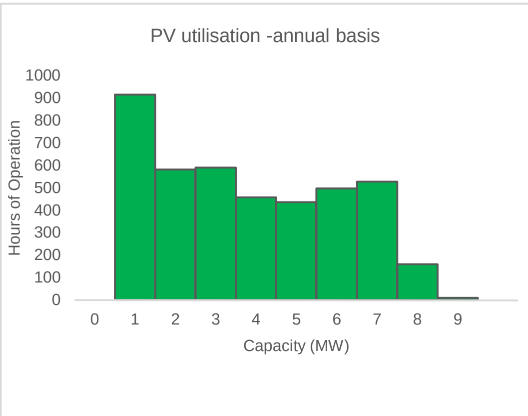

Figure 59: Wind capacity annual distribution

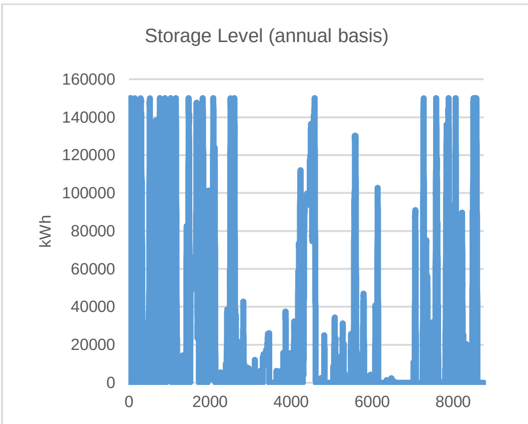

Figure 60: Storage operation annual basis

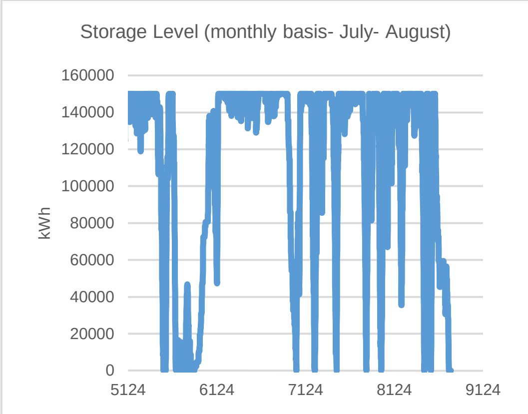

Figure 61: Storage operation monthly basis

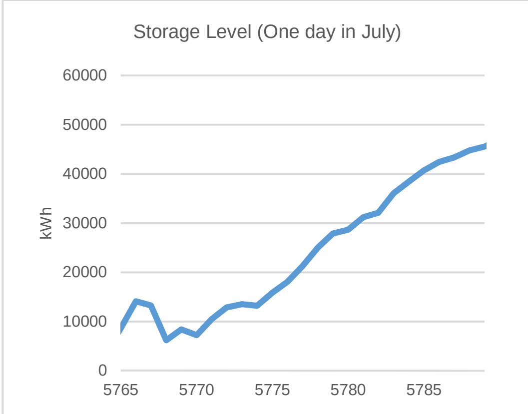

Figure 62: Storage operation daily basis

6.3.3 Operational model with binary variables extension

Often, in energy planning problems, discrete phenomena are encountered, i.e. facility selection for power generation. In such type of problems, some of the decision variables should be represented by integer and/or binary (0-1) variables. To that end proving the model adaptability and applicability to real world energy problems a binary variable is introduced $Br_{t,r}$ in the operational model allowing in each time step to select the most sustainable resource for power production (in our case the selection is made among the set of existing resources: wind vs PV vs diesel). The goal is to meet an additional load demand of 10% (an additional consumer, Figure 63) by mobilising either a diesel plant with similar capacity and characteristics as the existing or a wind or an PV similar however of larger scale plants. Energy storage, is not comprised is this optimisation scenario. GHG emissions' reduction goal $GHGmax$, is also applicable in this model variation.

Model statistics for this scenario include 18 blocks of equations, 140,166 single equations, 12 blocks of variables, 87,606 single variables, 26,280 diescret variables generation time 5.860 seconds, and memory usage 31 Mb. CPLEX solver was used. Results from otpimisation are illutsrted below (Tables 11,12, Figures 63-65):

Table 11: Overall and distinctive values for scenario with energy storage inclusion

Overall value (€)	Economic (€)	Environmental (€)	Social (€)
-265,549	-549,095	-39,454	-208,895

Table 12: Annual energy production from the set of resources

Diesel (kWh)	Wind (kWh)	PV (kWh)
3,169,629	28,436,451	4,655,395

So, under the scenario considered, the model selects wind energy SC, following the same pattern with the requested load demand as it is the most sustainable solution. However, due to capacity limitations PV and diesel are mobilised additionally in some instances as well, but with as quite small penetration rate through the year (Figures 64,65, Table 12).

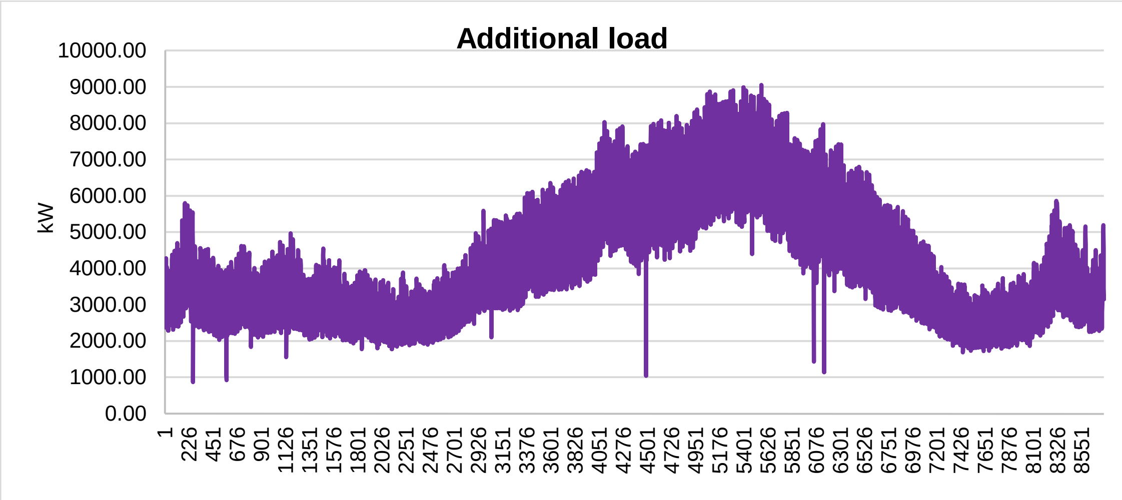

Figure 63: Additional load demand

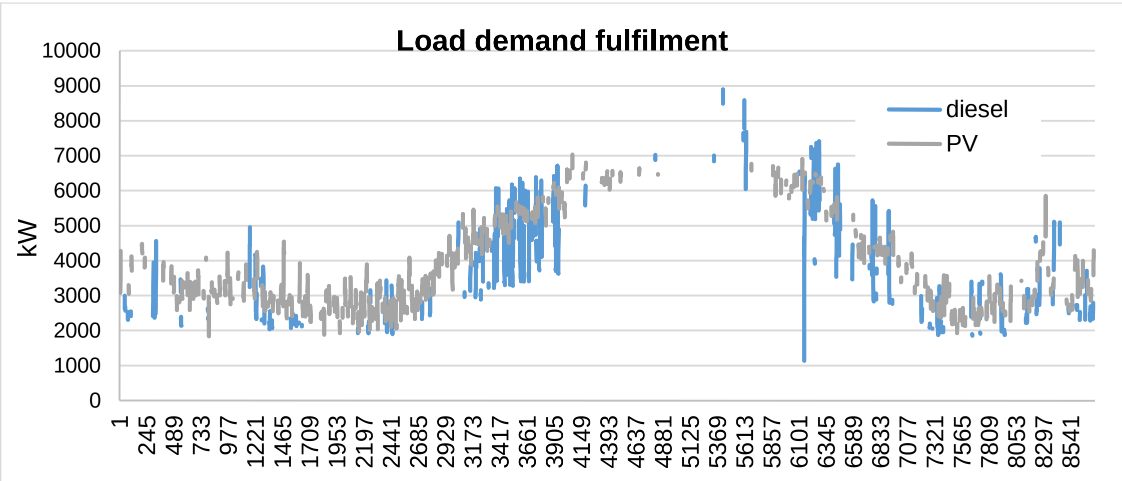

Figure 64: Load demand fulfilment – diesel , PV

The applicability of this type of model version could be better demonstrated in the case of large scale and complicated energy systems, whereas there would be multiple fossil based energy supply resources i.e., natural gas fired, diesel with different capacity factors etc and the model would choose which one to operate accounting in each case the technical limitations of the system.

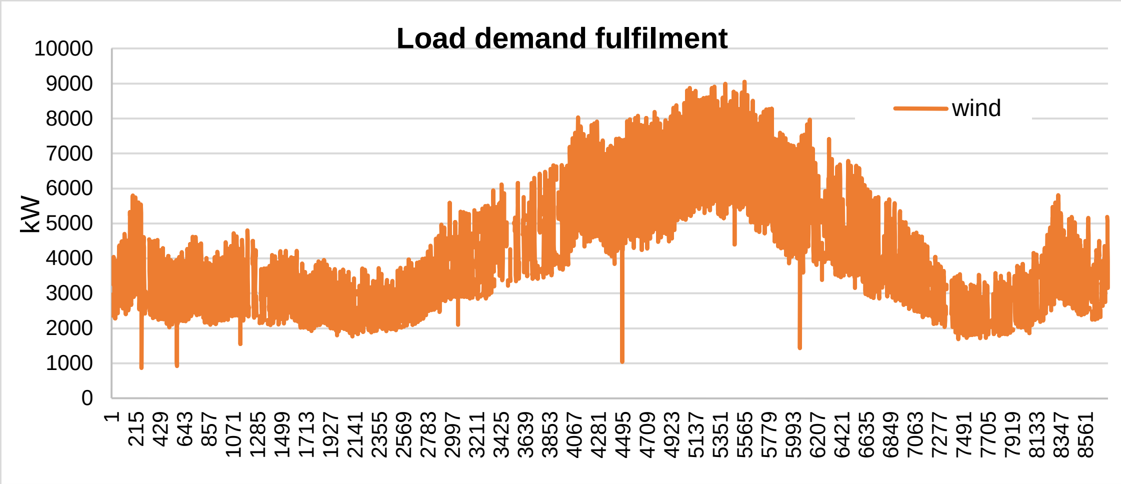

Figure 65: Load demand fulfilment –wind

Also what is very interesting to be noticed is the time –step of the planning horizon: under the availability of information for different time intervals – different decisions based on a binary criterion maybe made. In Figures 66-68 the load demand fulfilment variation according to the time-horizon of the examined problem is illustrated. Under a small snapshot i.e. as in Figure 68 the wind supply option may not be included at all as a possible solution to the problem under investigation. The same interpretation applies for Figures 66, 67.

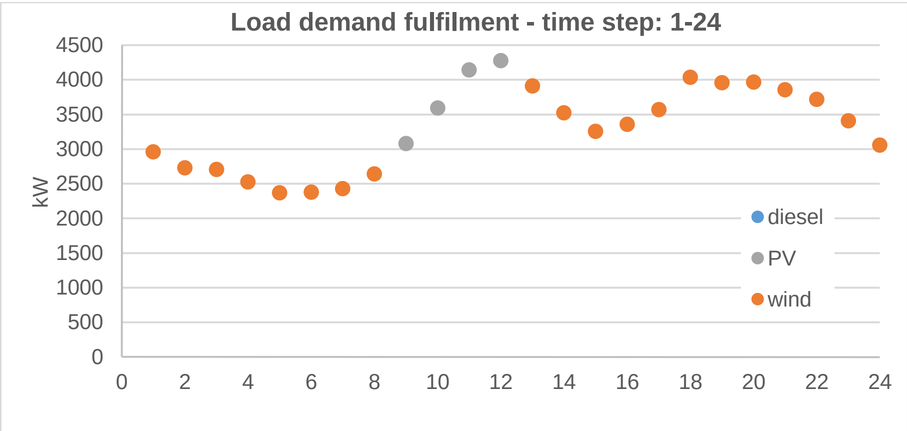

Figure 66: Load demand fulfilment – time step:1-24

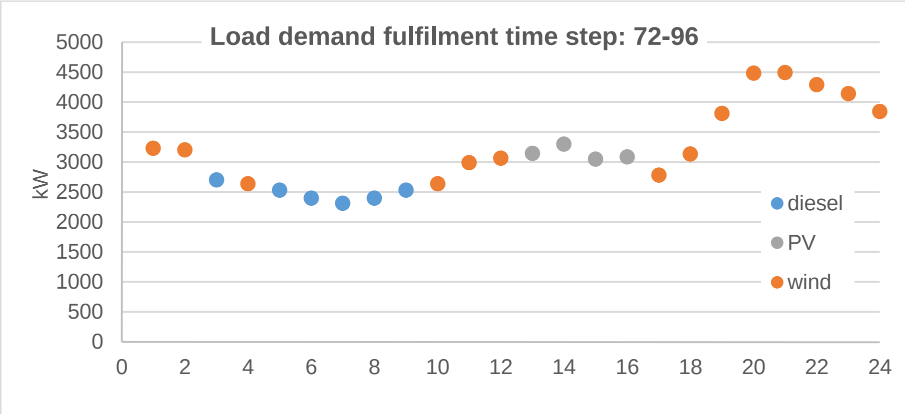

Figure 67: Load demand fulfilment – time step:72-96

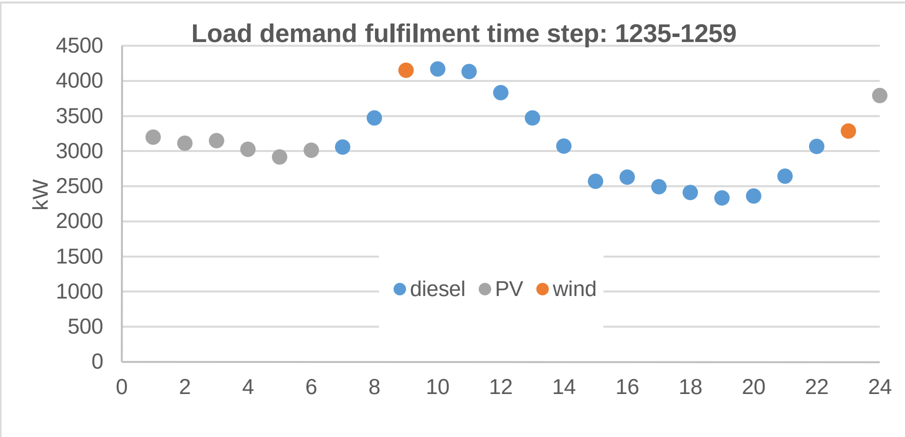

Figure 68: Load demand fulfilment – time step:1235-1259

6.3.4 Set of islands: large-scale investment optimisation

In this model version the preliminary design of a wind-PV-diesel -storage ESC configuration is examined. Input to the optimisation model is the time-varying demand, whilst in the side of plants/ resources availability the model accepts the respective capacity factors.

Two scenarios are considered to prove model implementation: a business as usual with no strict air quality limitations and an environmentally friendly scenario investigating the demand fulfilment with use only of renewable energy sources. Results are illustrated in the sequent sections. Model statistics for this set of scenarios include 19 blocks of equations, 140,167 single equations, 13 blocks of variables, 61,330 single variables, generation time 4.547 seconds, and memory usage 31 Mb. The solver used was CPLEX version 12.6.

6.3.4.1 Assessment of a typical wind, PV, diesel and energy storage configuration

Results from model optimisation for the investment planning model are described below (Tables 13,14):

Table 13: Power plants capacities for typical investment planning scenario

Diesel (kW)	Wind (kW)	PV (kW)	Storage (kWh)
43,896	155,635	116,395	$Ps_s = 200,000kWh$ $Psg_s = Psp_s = 50,000kWh$

Table 14: Overall and distinctive values for typical investment planning scenario

Overall value (€)	Economic (€)	Environmental (€)	Social (€)
8,785,111	8,691,460	-1,708,620	19,398,875

Modelling results include the optimum system sizing i.e. the developed model returns the optimum capacity of each of the contributing electricity generation plants as well as of the storage station. Under the optimisation target of the maximisation of the total value, an ESC configuration largely consisting of wind and PV power plants (Table 13, Figures 69-71) is proposed (resulting a positive overall value of the proposed configuration (8,785,111€, Table 14). A technical clause to this scenario due to the particularity of operational characteristics of the island network is the inclusion of the energy storage option.

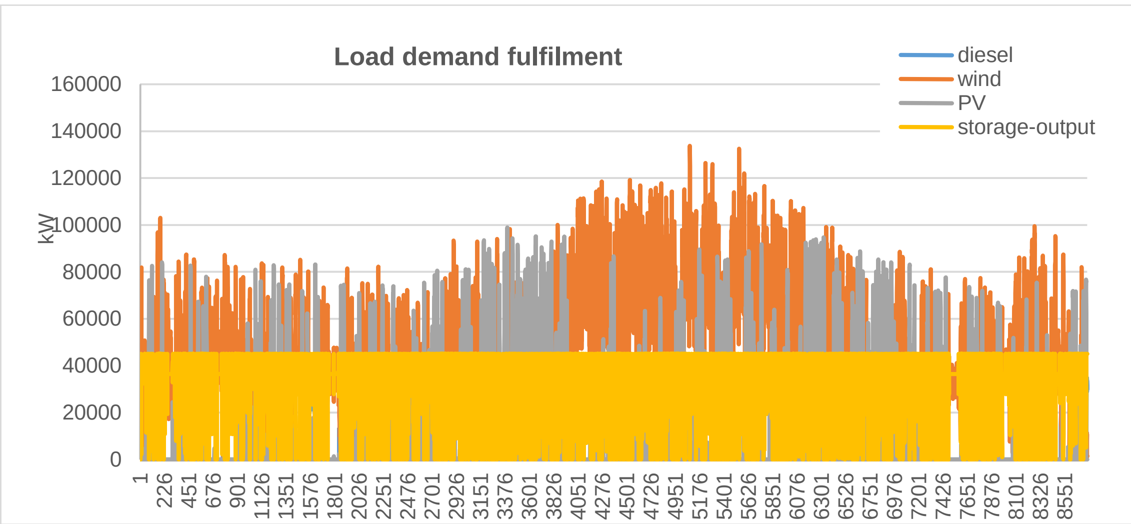

Figure 69: Load demand fulfilment

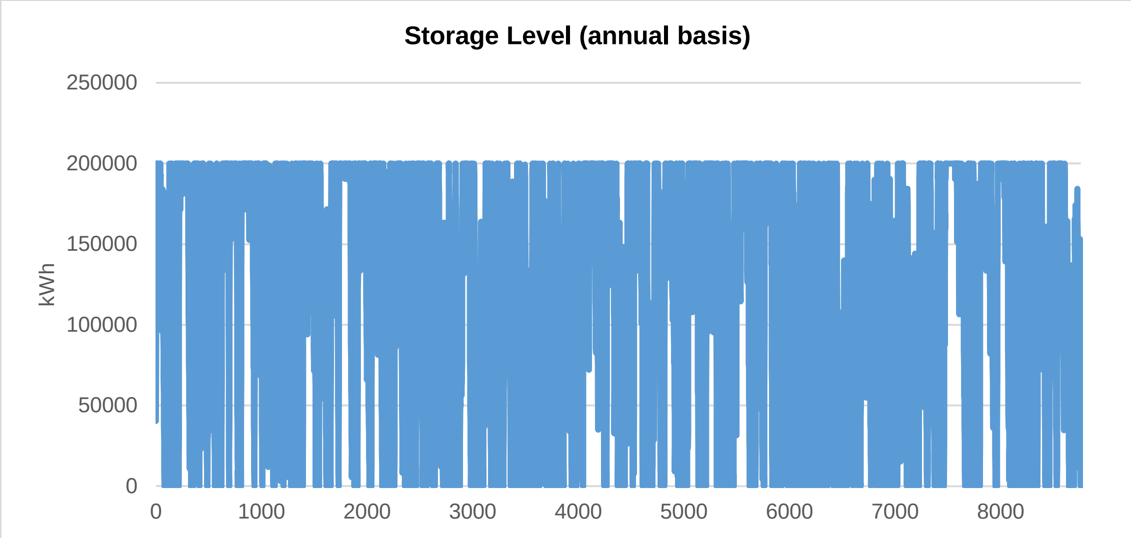

Figure 70: Storage operation on annual basis

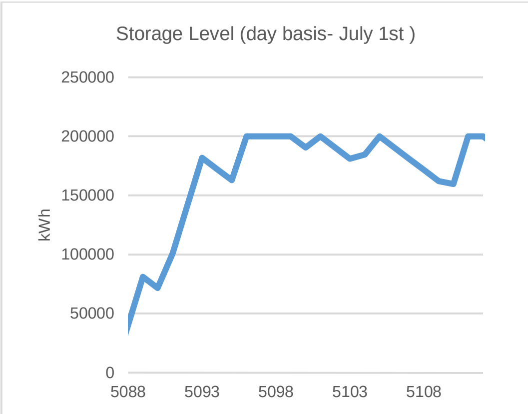

Figure 71: Storage operation daily basis

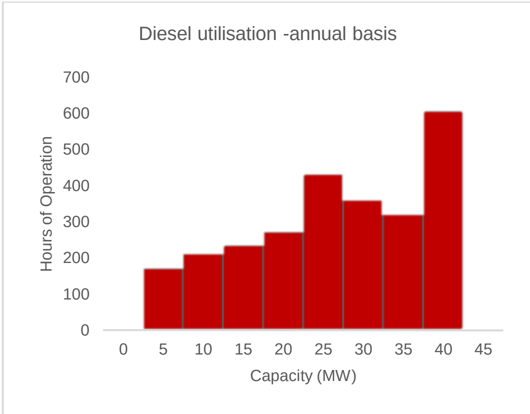

Figure 72: Diesel capacity annual distribution

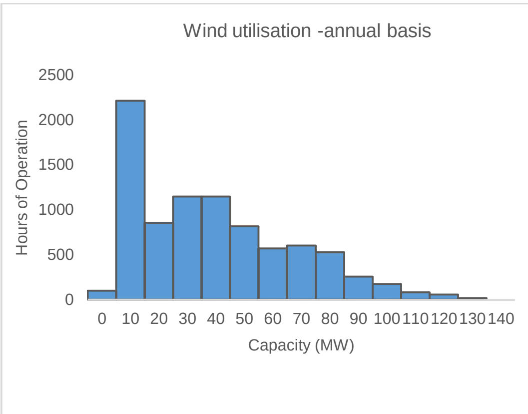

Figure 73: Wind capacity annual distribution

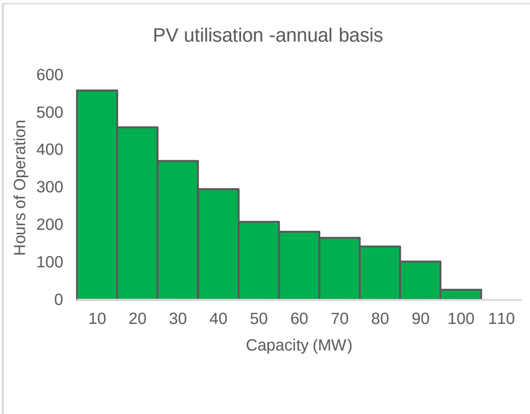

Figure 74: PV capacity annual distribution

Regarding Figure 70, the respective state of charge of the storage system is shown. According to the resulting profile, the frequent operation of the storage station is reflected, largely owed to the fact that the examined configuration employs all three generating sources (wind, PV and diesel). In such cases, the requirement for storage capacity is not as considerable, compared with wind-storage or PV-storage only cases, where absence of complementary power generating sources requires significant increase of the storage capacity. At the same time, the state of charge profile also reflects the frequency of operation of the storage system, or differently put the level of utilization of the system. To this end, it becomes evident that results obtained also favour increased capacity factor of the storage devise which can be considered as equivalent to a more cost-efficient system.

Concerning the operational characteristics of the configuration in total, power plants annual capacity distributions present very good utilisation rates evidencing the system optimum sizing (Figures 71-74). Results are calculated on the basis of one year but they may equally well address a longer time period i.e. for 20 years which is a typical time horizon for energy related projects, thus evidencing more representative plant sizes under the examined cases.

6.3.4.2 RES –based scenario "clean air"

In this modification of the originally applied investment scenario, the energy demand fulfilment is considered to be met under the contribution only of RES-based electricity generation plants, given a time varying solar and wind energy availability. Again in this scenario the decision variables are the capacities of the power plants operating under the clause of energy storage support, allowing large RES penetration rates in the network. Results concerning system sizing as well as the overall system's value are illustrated below (Tables 15,16, Figures 75-80):

Table 15: Overall and distinctive values for RES –based scenario

Overall value (€)	Economic (€)	Environmental (€)	Social (€)
-29,762,122	-111,450,676	-1,194,969	23,269,903

Table 16: Power plants capacities for RES –based scenario

Diesel (kW)	Wind (kW)	PV (kW)	Storage (kWh)
-	1,136,662	850,303	$Ps_s = 200,000 kWh$ $Psg_s = Psp_s = 50,000 kWh$

Commenting on the results, the proposed energy planning solution is heavily relied on wind which is more preferable than PV due to its overall economic and environmental better performance as indicated in the parameters set up. Despite the fact that the economic value of the system is considerably high due to the high investment cost of RES based plants, the social value of the system is also high, which results to a positive impact that may arise from the implementation of an assorted configuration. (Table 15, Figure 75). Looking at the operational side of the proposed configuration, energy storage serving on the side of security maximisation, is kept fully charged for the greater part of the year, however continuously exchanging energy with the network through the operation of charging and discharging (76-78). Wind and PV present also a balanced operation along the year, fact that derives from the system optimum sizing (Figures 79,80).

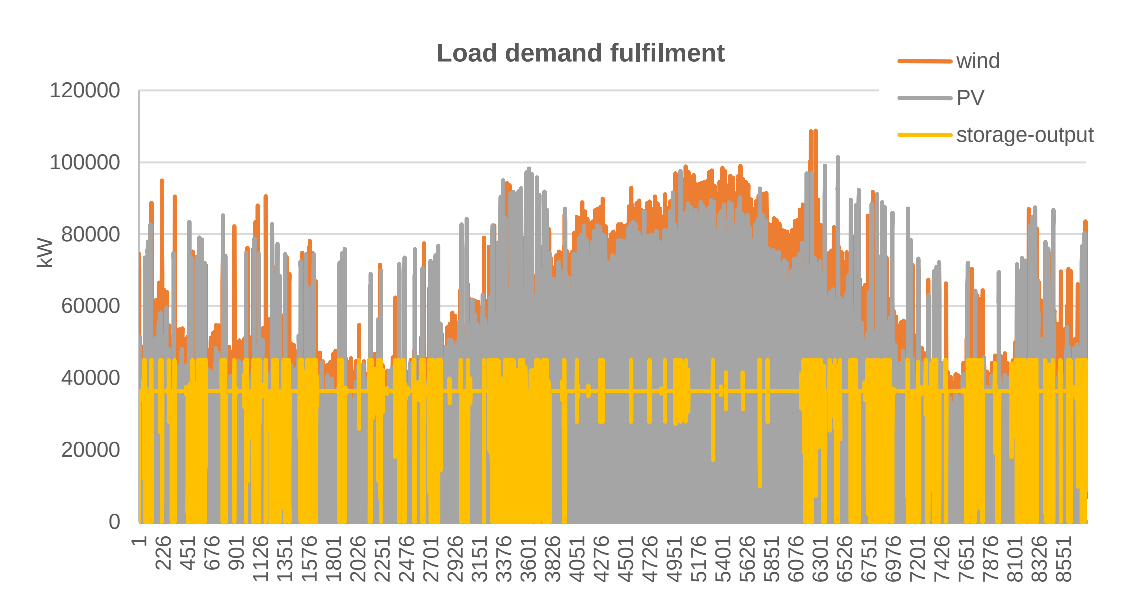

Figure 75: Load demand fulfilment

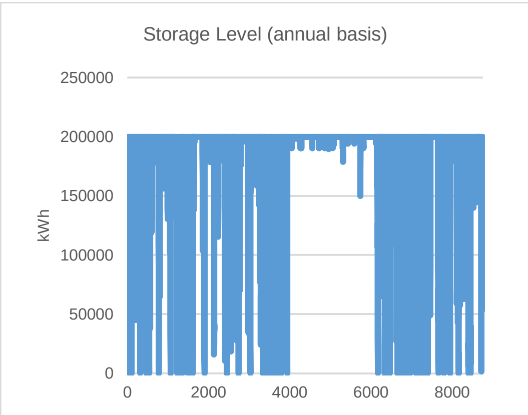

Figure 76: Storage operation annual basis

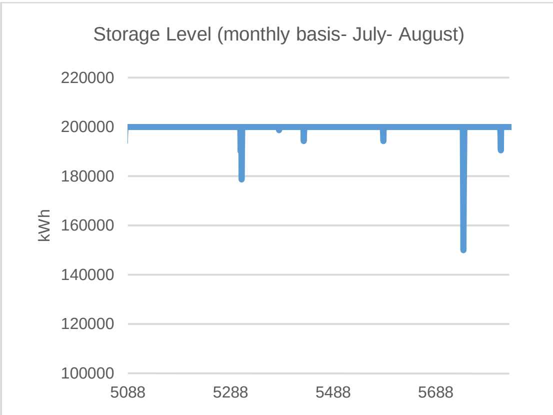

Figure 77: Storage operation monthly basis

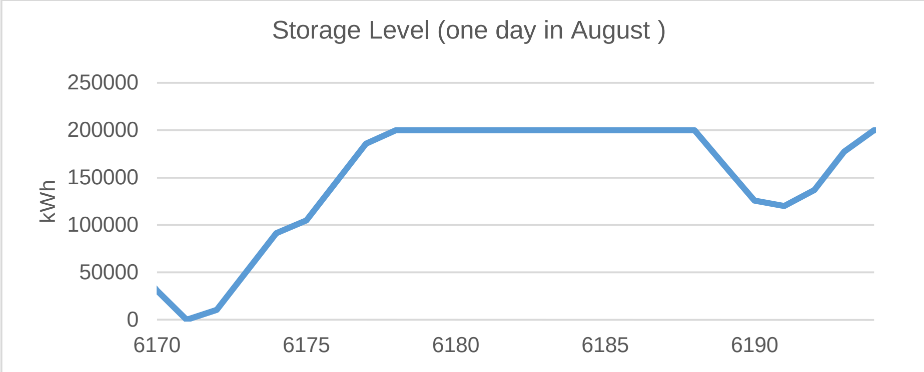

Figure 78: Storage operation daily basis

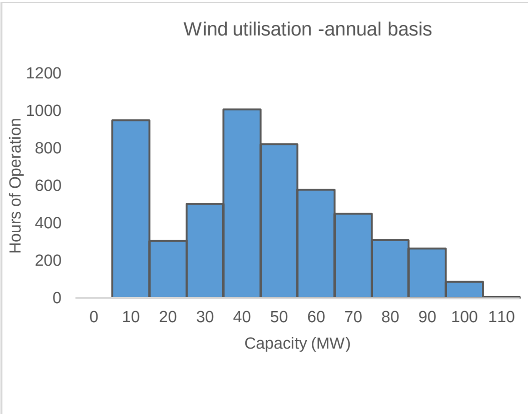

Figure 79: Wind capacity annual distribution

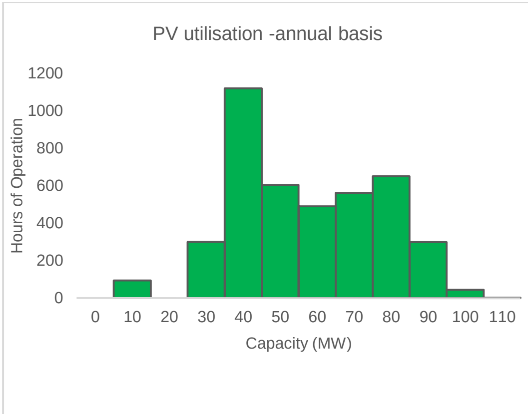

Figure 80: PV capacity annual distribution

This scenario evidences, that RES introduction is mainly hindered by techno-economic limitations that are dominant in the present energy decision making framework. Switching the policy objectives to include to maximisation of security of energy supply and environmental considerations equally weighted with relevant investment costs, can result future, sustainable ESC configurations.

6.4 Analysis of the findings

In this section, the developed approach will be discussed on the basis of analysing the results and providing also a sensitivity analysis of the critical parameters of the system. Results from the scenarios of set of islands are discusused here. Figure 81 provides a synoptic graph of the overall as well as the distinctive values, resulted from oprimisation for the different scenarios for the set of islands from Ch. 6.3. The values show the contribution to the respective cost function of each dimension, and the value of the weighted mean cost function. We should keep in mind in the interpretation of the results the primary definitions of objective values:

- Economic value considers the Total Costs (TC) of the electricity generation - (Investment, Maintenance and Operational Costs, Fixed Annual Cost) plus the Incomes from selling the electricity generated to the network operator (€)- so it can be positive
- Environmental value considers the environmental positive impact of the ESC in Life Cycle Analysis compared to an environmental – non friendly fossil based ESC with the a “typical-average” impact on the environment- so in the best case which is of wind resource the optimum value equals to zero
- Finally, the Social value of the ESC considers micro and macro – economic benefits from the implementation and operation of the different ESC configurations (€), so of positive value as well.

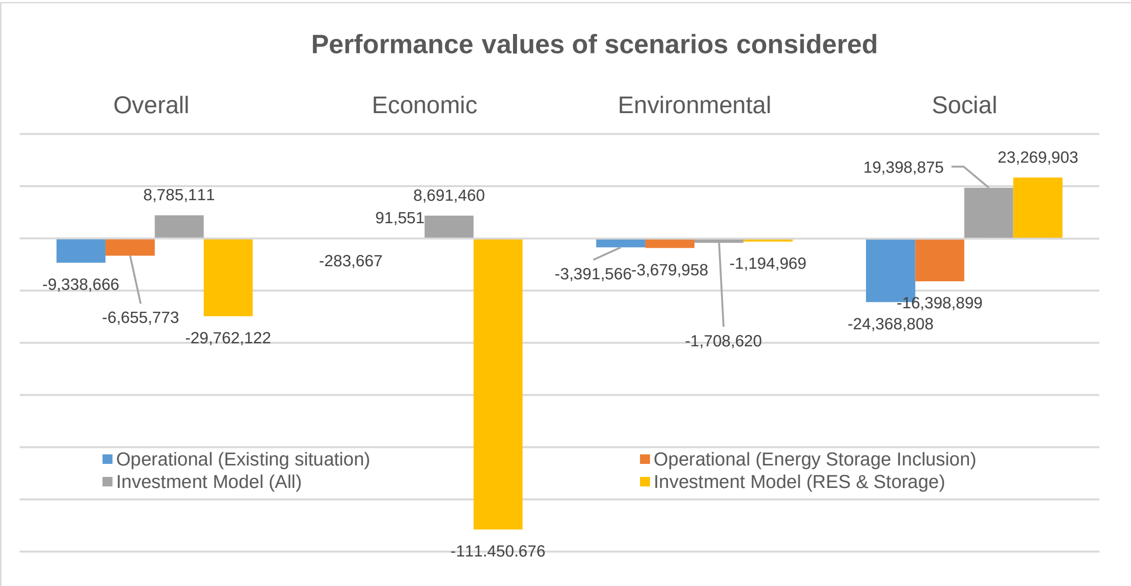

Figure 81: Performance values of the different scenarios considered

As one may see, the best energy planning solution, in terms of equal consideration of the different sustainably dimensions applied, is represented by the investment scenario with all the available resources being used. This set of SCs with the inclusion of a small diesel generation plant (compared to the existing plant-size) has a positive economic value whilst a relatively high social one due to the high penetration rate of wind and PV in the final demand. Of course it is obvious that the current situation represented by the operational scenario has the worst scores for all the criteria examined, because as it almost entirely based on fossil fuel (diesel) it presents a very negative social value (as there is total resilience on imported energy).

It is interesting also to note that the RES based scenario, although reflecting the social local optimum in the area under examination, due to its relatively high investment cost ranks as the 2nd best solution. However, even in the case of small modifications of the current ESC structure, only with the inclusion of an energy storage plant, which could be subsidised by the state, the overall score as well as each one of the single values can ameliorate significantly: diesel plant is down-sized, whilst wind-plant is oversized on top of the security supply accomplishment by the energy storage station introduction which serves on the side of minimisation of exchange losses due to imported oil.

What it must also be noticed, justified by Figure 81, is that with the traditional techno-economic considerations, values reflecting environmental implications of the designed SCs as well as the social impact both in terms of Micro and Macro social benefits are totally ignored and may lead to significant misjudgements. For example, for the RES-based “clean air” investment scenario, if only considering the techno-economic aspects the decision would be not to proceed to the specific investment whilst in terms of Social welfare it presents the best score.

This justifies the selection/introduction of the proposed modelling approach of multi-objective optimisation for the assessment of the energy planning problem: under a single objective optimisation model the decision making analysis may present significant shortcomings. Another significant contribution of the proposed approach, is the optimisation of resource-based annual electricity production: trans-passing through the different scenarios considered, we do achieve a better utilisation rate for renewables (including the energy storage option) along with more prominent overall system values (Figure 82).

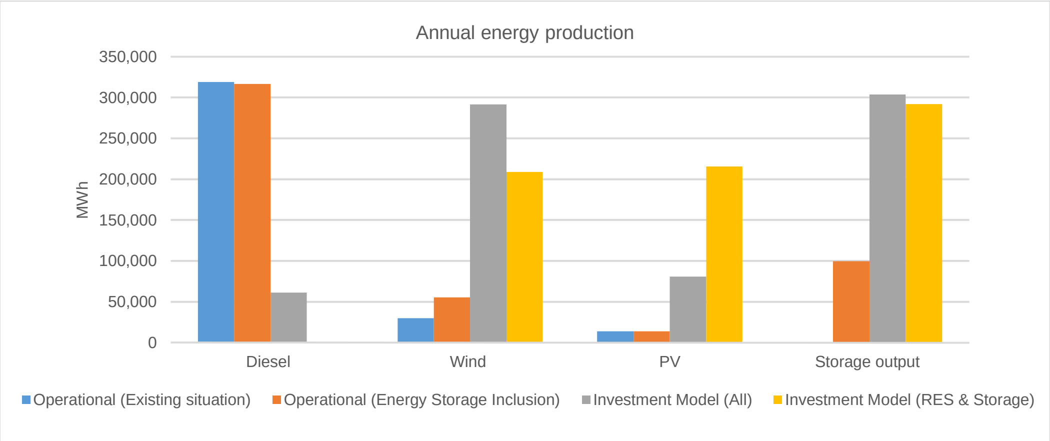

Figure 82: Annual electricity production by the set of available resources

6.5 Sensitivity analysis

Sensitivity analysis was carried out in order to identify and quantify uncertainties in the model results with respect to key parameters representing all three dimensions of the problem. The analysis was made for the basic investment scenario of wind-PV-diesel-energy storage configuration (Ch. 6.3.4.1) which, in the author's opinion, is the most "realistic" scenario. Four critical parameters were considered, each of one is varied up or down by amounts of ±50%, ± 25% and ±10% reflecting realistic possible ranges:

Economic parameters

- Electricity purchase cost from the energy storage station
- Resources capital cost (and the associated annual fixed cost)

Environmental

- CO_2 emission price evolution

Social

- Exchange losses from imported energy

In Tables 17-20, the influence of parameters in the overall value is illustrated: the red column presents the initial values, on its right the positive deviation and on the left the negative ones. All inputs are marked with grey whilst the resulting values with black. Briefly all the results are also listed in Table 20.

In Figure 83 an illustration of the resulting values of the sensitivity analysis as a function of the initial objective function (i.e. for the economic parameter P_{EL2} in -50% the respective value equals to 17,531,000 / 8,785,111 $\approx$2) evidencing the deviation in terms of magnitude on the optimisation criterion.

Table 17: Economic parameters considered for sensitivity analysis

Deviation scales	-50%	-25%	-10%	0	10%	25%	50%
ECONOMIC							
P_{EL2}	Electricity purchase cost from the energy storage station						
Storage (€/kWh)	0.070	0.105	0.126	0.140	0.154	0.175	0.210
Overall value (€)	17,531,000	13,155,000	10,533,000	8,785,111	7,047,500	5,322,700	3,432,700
$INV_{r,s}$	Resources capital cost						
Wind (€/kW)	36.500	54.750	65.700	73.000	80.300	91.250	109.500
PV (€/kW)	40.000	60.000	72.000	80.000	88.000	100.000	120.000
Diesel (€/kW)	28.500	42.750	51.300	57.000	62.700	71.250	85.500
Storage (€/kWh)	21.500	32.250	38.700	43.000	47.300	53.750	64.500
$F_{Cr,s}$	*Resources annual fixed cost*						
Wind (€/kWh)	0.365	0.548	0.657	0.730	0.803	0.913	1.095
PV (€/kWh)	0.400	0.600	0.720	0.800	0.880	1.000	1.200
Diesel(€/kWh)	1.140	1.710	2.052	2.280	2.508	2.850	3.420
Storage (€/kWh)	0.430	0.645	0.774	0.860	0.946	1.075	1.290
Overall value (€)	14,552,000	11,551,000	9,867,000	8,785,111	7,726,800	6,179,600	3,677,700

Table 18: Environmental parameters considered for sensitivity analysis

Deviation scales	-50%	-25%	-10%	0	10%	25%	50%
ENVIRONMENTAL							
PCO_2 (€/kWh)	0.008	0.011	0.014	0.015	0.017	0.019	0.023
Overall value (€)	9,070,100	8,927,400	8,842,000	8,785,111	8,728,200	8,642,900	8,500,600

Table 19: Social parameters considered for sensitivity analysis

Deviation scales	-50%	-25%	-10%	0	10%	25%	50%
SOCIAL							
PEX (€/kWh)	0.039	0.0585	0.0702	0.078	0.0858	0.0975	0.117
Overall value (€)	6,152,400	7,223,800	8,157,400	8,785,111	9,414,500	10,362,000	11,953,000

Table 20: Overall values resulting from parameters' sensitivity analysis

Deviation scales	-50%	-25%	-10%	0	10%	25%	50%
Storage cost: P_{EL2}	17,531,000	13,155,000	10,533,000	8,785,111	7,047,500	5,322,700	3,432,700
Investment costs	14,552,000	11,551,000	9,867,000	8,785,111	7,726,800	6,179,600	3,677,700
Carbon costs: PCO_2	9,070,100	8,927,400	8,842,000	8,785,111	8,728,200	8,642,900	8,500,600
Social costs, PEX	6,152,400	7,223,800	8,157,400	8,785,111	9,414,500	10,362,000	11,953,000

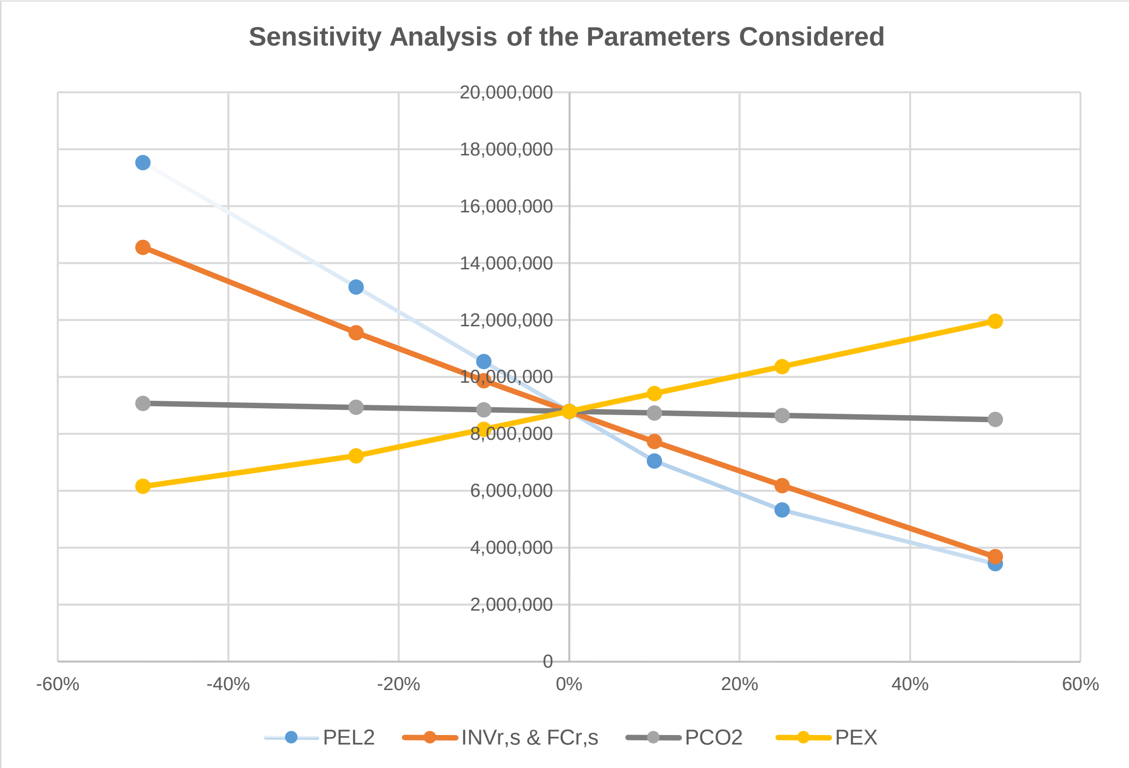

Figure 83: Impact of the selected parameters on the objective function

6.5.1 Impact of the electricity purchase cost from the energy storage station

Electricity purchase cost from the energy storage station seems to have the most significant impact on the overall value of the system. If the storage system buys "cheap" energy then due to the specific configuration (of the energy storage inclusion), it creates a great margin for profit maximisation. This is something that could be investigated in real market situations with a time-varying electricity purchase cost profile. More precisely, considering a range of variation from -50% to 50% in order to also capture long-term changes of the input electricity price, the corresponding effect on the objective function values is described by a considerable change from 17.5ME to 3.7ME.

6.5.2 Impact of the Resources capital cost (and the associated annual fixed cost)

Resources capital cost (and the associated annual fixed cost) has a similar behaviour with the other economic parameters examined. If relative subsidisation of the plants (especially the “expensive” RES-based) could apply, that could lead to a greater margin for profit maximisation. To this end, considering a range of variation from -50% to 50% to also capture the cost of different technological solutions as well as the vasty decreasing capital costs of certain technologies (e.g. battery storage), the corresponding effect on the objective function values is described by an inconsiderable change from 14.5ME to 3.7ME.

6.5.3 Impact of the CO_2 emission price evolution

CO_2 emission price evolution seems to have negligible impact on the optimisation criterion. This can be explained by taking into account the fact that the only GHG emitting plant in the case study is the diesel electricity generation. It would be interesting to investigate the CO_2 emission price impact in the case that there exist multiple fossil based facilities (i.e. natural gas, lignite and diesel), of different technologies, resulting different emission factors. In this context, considering a range of variation from -50% to 50% so as to capture different emission factors as well as a differentiation in the price of CO_2 allowances, the corresponding effect on the objective function values is described by a considerable change from from 9.1ME to 8.5ME.

6.5.4 Impact of the Exchange losses from imported energy

The Value of exchange losses from imported energy (and resources) has also significant impact on the final optimisation value obtained. As one may see from Figure 83, low-cost imported energy has a direct effect on the social value obtained and at the same time encourages diesel imports in our case, whilst also discourages the investment on a local storage station (SEC indices -1, 1 according) limiting actually the real penetration rate of RES. On the other hand, if facing a high price for oil imports, the model reacts and avoids such imports, increasing thus the energy security and social value that in turn leads to the maximisation of the objective function value. In this context, considering a range of variation from -50% to 50% so as to capture the price volatility of fuel imports, the corresponding effect on the objective function values is described by a considerable change from 6.15ME to 11.95ME.

Furthermore, an alternative illustration of the results is provided in Figure 84, demonstrating that the variation of the involved parameters leads to the identification of the area of 5-10ME for the objective function as the most expected one. At the same time, expectancy of the extreme edges, i.e. below 5ME and above 15ME is in any case quite narrow and could be thought as of minor probability.

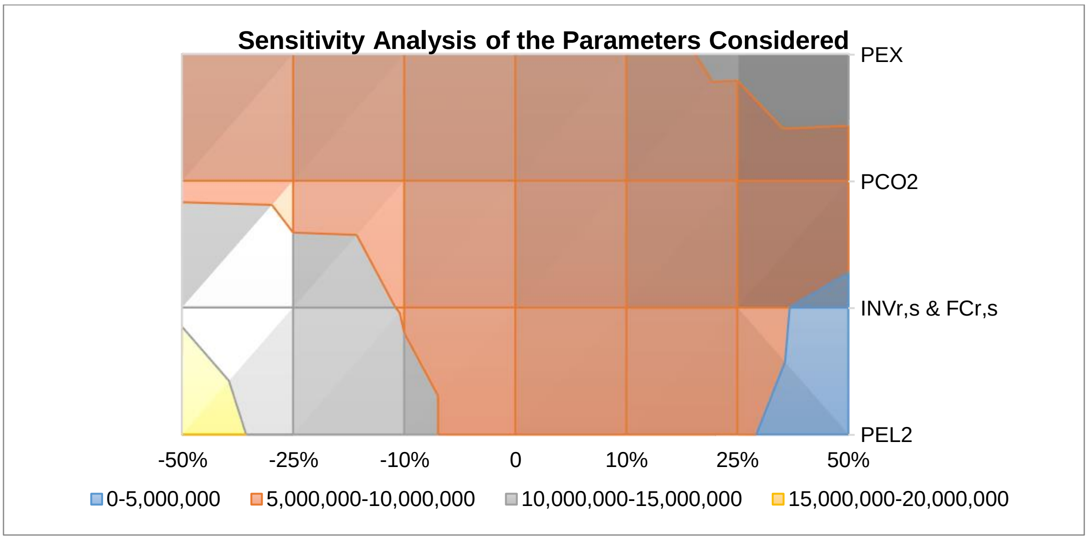

Figure 84: Impacted areas of the selected parameters in the objective function

6.5.5 Impact of the Weights

One of the most common difficulties dealt with the weighted sum method is that weights variation consistently and continuously may not necessarily result in an accurate, complete representation of the Pareto optimal set. This deficiency can seriously puzzle the energy decision making process because the optimal solution may present huge jumps in the case of slight changes of the weights and remained unaffected with broader changes.

Seeking to investigate that, different values in the weights will be investigated: each of the weights (a_1, a_2, a_3) is increased by 0.1 (with the starting point being the values initially set in the problem under investigation i.e. 0.333) and the rest two are considered of equal importance: for example when, $a'_1 = 0.333 + 0.100 = 0.433$ a'_2, a'_3 can be calculated by the following formula: $a'_2 = a'_3 = \frac{1.000 - 0.433}{2} = 0.284$. Calculation results are illustrated in Figure 85. As one may observe both a_1, a_3 increase implies the optimisation criterion increase as well, with the opposite outcome occurring for a_2 increase. To this end, it is important to note that increase of the importance of the environmental weight factor gradually leads to the reduction of the objective function value. This can be explained by the fact that the environmental function *ENVV* receives negative values for systems presenting a footprint different to the reference one (i.e. the one of wind). Furthermore, by increasing the significance of the a_2 coefficient, the model gradually neglects the economic and social behaviour of the system and thus leads to negative objective function values justified by the need to support wind energy production with PV, storage and diesel, which implies a negative final outcome (see also the equation of the objective function presented earlier).

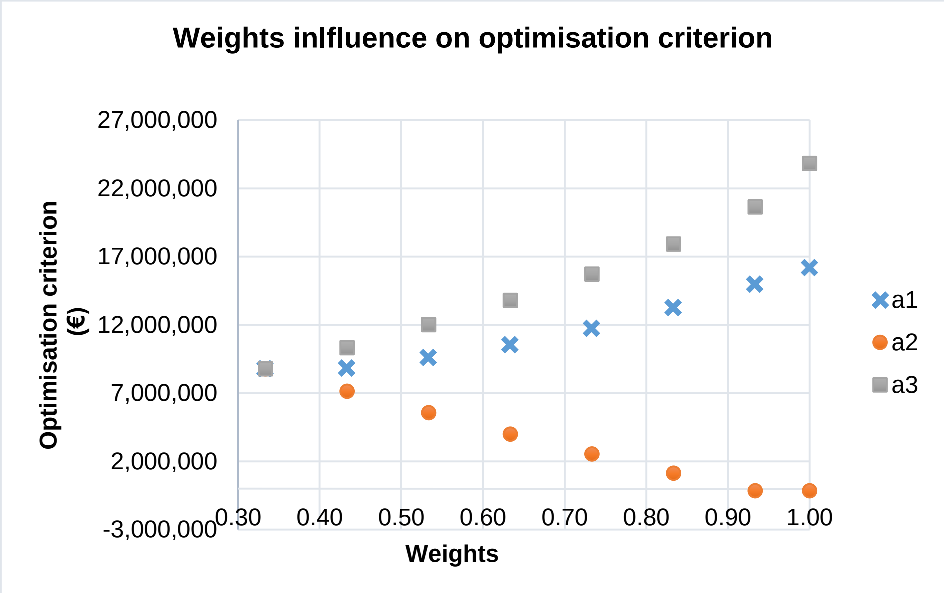

Figure 85: Weights influence on the optimisation criterion

In the same context, an alternative illustration can be used in Figure 86 to also present the effect of the relative increase of weight factors (i.e. from 33% to 100% by a step of 10%) on the relative increase/decrease of the objective function value. To this end, the sensitivity of the objective function is revealed in relation to all three parameters, with the respective range of variation being -100% to +170%, reflecting also the need to properly determine the respective values when it comes to energy planning decision making processes.

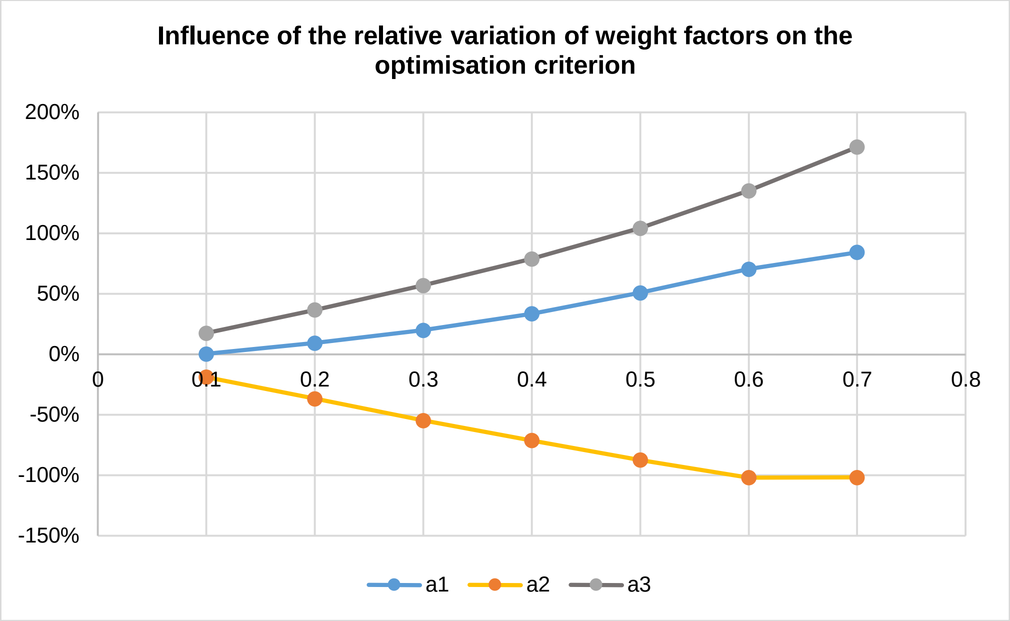

Figure 86: Influential behaviour of weights on a percentage basis

CHAPTER 7: CONCLUSIONS

In the present chapter the concluding remarks of the work will be presented. In addition, some future points for the continuation of the present work will be given as well.

7.1 Concluding remarks

Owing that to emerging complexities of the contemporary climate mandates and energy supply options, many conventional energy and fuel SCs are being re-designed and reassessed under that perspective, seeking to evaluate the multiple uncertainties deriving from the multi-criteria, multi-parameters, at multi-levels of decisions, in a multi-stakeholder's interactive environment.

However, although energy SCs is the subject objective of many researchers, association of technological issues with economic, social and environmental impacts has not been achieved yet. With the need to respond to that, the aim of the present thesis was to develop an evaluation framework for the assessment of alternative energy and fuel SCs. The evaluation framework consists of a suitable representation (tool), a set of appropriately selected and quantified parameters and indices addressing the sustainability dimensions and an appropriately formed mathematical model with primary objective being the maximisation of the total value of the system by accounting simultaneously techno-economic, environmental and social implications.

Seeking to assess energy planning problems with emphasis in the electricity supply, the need for a uniform representation of all the different energy and fuel SCs was identified. To that end the RTN representation, popularly used for formulating mathematical models of scheduling problems in process industries was adopted. RTN representation offered a unified treatment of different resources such as processing and storage units, material states and utilities.

Secondly, in the quest of efficiently addressing sustainability issues embedded in each alternative SC option, a matrix of indicators has been put on, acknowledging the widely applicable ones in energy planning problems, but also citing indices that have already been applied to energy and fuels SCs.

On the modelling formulation, a Multiobjective LP model is developed with the possibility/extension of including binary variables as well, in large scale scheduling problems with resources variation (MILP formulation). In our work, the optimisation criterion, expressed as the maximisation of the total value of the ESC configuration in terms of techno-economic, environmental and social implications, was formulated as a scalar function of the objectives considerd, by assigning equal preferences (relative weights).

Model implementation was carried out for different cases of electricity consumers (single island and set of island cases) in Greece, with emphasis on isolated island communities for multiple time-steps (day-month-year), under the detailed time-interval of one hour at the level of operation and strategic planning.

Results provided a thorough insight of the existing electricity supply, as well as different operational capabilities and systems sizes reflected by the introduction of sustainability dimensions.

Another interesting point and maybe innovative of the present research is the inclusion of the energy storage. It must be noticed that for the present research a typical energy storage/ battery system, was considered. Nevertheless, the model structure may also accommodate larger storage systems like pumped – hydro ones.

Model simulations were carried out in almost all the commercially available modelling platforms (Excel solver, Opensolver, Lindo What’s best) but for large time-scales only GAMS was used. Under the computational variations and input data, the model may result the optimum capacity for a set of resources and plants individually as well as the size of the energy storage system.

Also in its binary extension, the model, in each time step may select amongst the wide set of alternative and fuel SCs only the most sustainable one. This extension of the model may find a wide field of applicability in large-scale electricity scheduling problems, where there is a set of fossil based resources that must contribute in demand fulfilment in a specific way, with temporal variation and on selective basis.

Trying to address issues of uncertainties mainly relying on the parameters selected for the resolution of the multiobjective problem, a detailed sensitivity analysis was carried out for the basic parameters of model, for all the distinctive criteria (economic, social and environmental). Results evidenced their influential character on the optimisation criterion but also resulted a common space of solutions, inside which all the deviations could provide reliable output.

Furthermore, in order to identify hindered trade-off solutions in the single objective function of the model, different weights were tested: analysis derived a wide range of overall values, enlightening some scale of magnitudes between the objective values. This could be more thoroughly investigated into a further point of this research work.

Concluding, seeking to acknowledge the possible contribution of the work to the broader research field, one should consider:

a) The wide field of applications of the developed mathematical model formulated as Multiobjective Mixed Linear Programming Problem, which as it is very simple both in the implementation and in the interpretation of the results, and assumes only basic knowledge in computer programming and optimisation modelling, maybe used by a wide set of users in a wide set of case studies.

b) The possibility of model implementation into larger energy planning problems for bigger sets of consumers i.e. at strategic energy decision making at country level.

c) The proposed framework's transferability and expansion possibilities, because while it is tested for a set of electricity SCs, its generic nature of formulation allows its application to other type of SCs like the ones of energy and water. In addition, the building block structure of the framework foresees transferability to other countries as well as modification (expansion) to include the special characteristics of each future case study and decision maker's interests.

d) The adaptability of the optimisation criterion with the weighted factors in each special dimension, economic, environmental and social, provides the flexibility to the user to adjust his decision considering the special characteristics and needs of each energy planning problem.

All these attributes are resulting from the holistic consideration of different but interrelated aspects, economic, technical, environmental and social parameters and objectives, all incorporated into an optimisation criterion, and the implicit representation of the fossil and alternative energy and fuel SCs in a generic/ comparable topology.

7.2 Further work

As a continuation of the present modelling the following directions could be considered:

- Inclusion of more complicated economic functions with emphasis in the discounted cash flows as to result more reliable economic outputs.
- Application of the present model to larger time-scales i.e. 20 years, accounting for all the resources' life-time impact on the electricity fuel mix.
- Inclusion of more complicated ESCs structures with multiple resources and end users.
- Investigation and evaluation of the interconnection option at country level.
- Modelling of an electricity supply system with the inclusion of a large energy storage operation i.e. a pumped hydro storage for load balancing.
- Multiobjective problem assessment with ε-constrained method and possibly with goal programming for given values and goals for the system under investigation.
- Application of the model to another country to evidence the differences resulting in energy fuel mix accounting diverse energy policies and location specific parameters.

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APPENDIX A: Sustainable Development Indicators

APPENDIX A.1: List for sustainability criteria (European Commission, Directorate-General for Research, 2009)

Area	Theme	Subject
Environmental	Climate Biodiversity Local environmental effects	GHG balance Carbon sinks Biodiversity Air quality Soil quality and erosion Water quality and resources management
Social	Social well-being	Health and safety Paying and working conditions Women's rights No discrimination
Economic	Local economic effects Economic sustainability	Local prosperity Long terms economic and financial viability
Other	Competition with food/ other indirect effects of land use change Governance	Food competition Transparency Land use rights Waste reduction Continuous improvement in social and environmental aspects Environmental impacts and social assessment of planning and implementation

APPENDIX A.2: Eurostat Sustainable Development Indicators (European Commission, Directorate-General for Research, 2009)

Theme 1: Socio-Economic Development

Level 1	Level 2	Level 3
1. Growth rate of GDP per inhabitant	**Sub-theme: ECONOMIC DEVELOPMENT**	
	2. Total investment	5. Dispersion of regional GDP per inhabitant
	3. Public investment	6. Net national income
	4. Business investment	7. Gross household saving
	Sub-theme: INNOVATION, COMPETITIVENESS AND ECO-EFFICIENCY	
	8. Growth of labour productivity per hour worked	9. Total R&D expenditure
		10. Real effective exchange rate
		11. Turnover from innovation
		12. Effects of innovation on material and energy efficiency
		13. Energy intensity of the economy
		14. Effects of innovation on reduced environmental impacts or improved health and safety
	Sub-theme: EMPLOYMENT	
	15. Employment rate	16. Employment rate, by gender
		17. Employment rate, by highest level of education attained
		18. Dispersion of regional employment rates, by gender
		19. Unemployment rate, by gender
		20. Unemployment rate, by age group

Theme 2: Sustainable Consumption and Production

Level 1	Level 2	Level 3
1. Resource Productivity		
	Sub-theme: RESOURCE USE AND WASTE	
	2. Municipal waste generated	3. Components of domestic material consumption
		4. Domestic material consumption by material
		5. Municipal waste treatment, by type of treatment method
		6. Generation of hazardous waste, by economic activity
		7. Emissions of acidifying substances by source sector
		8. Emissions of ozone precursors by source sector
		9. Emissions of particulate matter by source sector
	Sub-theme: CONSUMPTION PATTERNS	
	10. Electricity consumption by households	11. Final energy consumption by sector
		12. Consumption of certain foodstuffs per inhabitant
		13. Motorisation rate
	Sub-theme: PRODUCTION PATTERNS	
	14. Organisations with an environmental management system	15. Eco-label awards
		16. Area under agri-environmental commitment
		17. Area under organic farming
		18. Livestock density index
Contextual indicators	- Number of households - Household expenditure per inhabitant, by category	

Theme 3: Social Inclusion

Level 1	Level 2	Level 3
1. At-risk-of-poverty rate, by gender	**Sub-theme: MONETARY POVERTY AND LIVING CONDITIONS**	
	2. At-persistent-risk-of-poverty rate	3. At-risk-of-poverty rate, by age group
		4. At-risk-of-poverty rate, by household type
		5. Relative at-risk-of-poverty gap
		6. Inequality of income distribution
	Sub-theme: ACCESS TO LABOUR MARKET	
	7. People living in jobless households, by age group	8. In-work poverty
		9. Total long-term unemployment rate
		10.Gender pay gap in unadjusted form
	Sub-theme: EDUCATION	
	11. Early school leavers	12. At-risk-of-poverty rate, by highest level of education attained
		13. Persons with low educational attainment, by age group
		14. Life-long learning
		15. Low reading literacy performance of pupils
		16. Individuals' level of computer skills
		17. Individuals' level of internet skills
Contextual indicator	- Public expenditure on education (for sub-theme Education)	

Theme 4: Demographic Changes

Level 1	Level 2	Level 3
1. Employment rate of older workers	**Sub-theme: DEMOGRAPHY**	
	2. Life expectancy at age 65, by gender	3. Total fertility rate
		4. Net migration including corrections
	Sub-theme: OLD-AGE INCOME ADEQUACY	
	5. Aggregated replacement ratio	6. At-risk-of-poverty rate of elderly people
	Sub-theme: PUBLIC FINANCE SUSTAINABILITY	
	7. General government debt	8. Average exit age from the labour market
Contextual indicators	- Old age dependency ratio (for sub-theme Demographic changes) - Projected old age dependency ratio (for sub-theme Demographic changes) - Public expenditure on care for the elderly (for sub-theme Public finance sustainability)	

Theme 5: Public Health

Level 1	Level 2	Level 3
1. Healthy life years and life expectancy at birth, by gender	**Sub-theme: HEALTH AND HEALTH INEQUALITIES**	
	2. Death rate due to chronic diseases, by gender	3. Healthy life years and life expectancy at age 65, bygender
		4. Suicide death rate, total by age group
		5. Suicide death rate, males by age group
		6. Suicide death rate, females by age group
		7. Self-reported unmet need for medical examination or treatment, by income quintile
		8. Dispersion of regional death rates (not yet available)
	Sub-theme: DETERMINANTS OF HEALTH	
	9. Index of production of toxic chemicals, by toxicity class	10. Population exposure to air pollution by particular matter
		11. Population exposure to air pollution by ozone
		12. Population living in households considering that they suffer from noise
		13. Serious accidents at work

Theme 6: Climate Change and Energy

Level 1	Level 2	Level 3
1. Greenhouse gas emissions	**Sub-theme: CLIMATE CHANGE**	
	3. Greenhouse gas emissions by sector (including sinks)	4. Greenhouse gas emissions intensity of energy consumption
		5. Projections of greenhouse gas emissions
		6. Global surface average temperature
	Sub-theme: ENERGY	
2. Share of renewables in gross inland energy consumption	7. Energy dependency	8. Gross inland energy consumption by fuel
		9. Electricity generated from renewable sources
		10. Share of biofuels in fuel consumption of transport
		11. Combined heat and power generation
		12. Implicit tax rate on energy

Theme 7: Sustainable Transport

Level 1	Level 2	Level 3
1. Energy consumption by transport mode	**Sub-theme: TRANSPORT AND MOBILITY**	
	2. Modal split of passenger transport	4. Volume of freight transport
	3. Modal split of freight transport	5. Volume of passenger transport
		6. Investment in transport infrastructure by mode *(not yet available)*
	Sub-theme: TRANSPORT IMPACTS	
	7. Greenhouse gas emissions by transport mode	8. People killed in road accidents
	9. Emissions of ozone precursors from transport	10. Emissions of particulate matter from transport
		11. Average CO_2 emissions per km from new passenger cars
	Contextual indicator	- Price indices for transport

Theme 8: Natural Resources

Level 1	Level 2	Level 3
1.Common Bird Index	**Sub-theme: BIODIVERSITY**	
	3. Sufficiency of sites designated under the EU Habitats directive	4. Deadwood *(not yet available)*
	Sub-theme: FRESH WATER RESOURCES	
	5.Surface and groundwater abstraction as a share of available resources	6. Population connected to urban wastewater treatment
		7. Biochemical oxygen demand in rivers *(not yet available)*
	Sub-theme: MARINE ECOSYSTEMS	
2.Fish catchestaken from stocks outside safe biological limits	8. Concentration of mercury in fish	9. Size of fishing fleet
	Sub-theme: LAND USE	
	10. Built-up areas	12. Forest trees damaged by defoliation
	11. Forest increment and fellings	13. Land at risk of soil erosion *(not yet available)*

Theme 9: Global Partnership

Level 1	Level 2	Level 3
1.Official Development Assistance as share of gross national income	**Sub-theme: GLOBALISATION OF TRADE**	
	2. EU imports from developing countries, by income group	3. EU imports from developing countries by group of products
		4. EU imports from least-developed countries by group of products
		5. Aggregated measurement of support *(not yet available)*
	Sub-theme: FINANCING FOR SUSTAINABLE DEVELOPMENT	
	6. Total EU financing for developing countries, by type	7. Foreign direct investment in developing countries, by
		8. Official development assistance, by income group
		9. Untied official development assistance
		10. Bilateral official development assistance by category
	Sub-theme: GLOBAL RESOURCE MANAGEMENT	
	11. CO_2 emissions per inhabitant in the EU and in developing countries	
Contextual indicators	- Population living on less than 1USD a day (for sub-theme Financing for SD) *(not yet available)* - Official development assistance per inhabitant (for sub-theme Financing for SD) - Population with sustainable access to an improved water source (for sub-theme Global Resource Management) *(not yet available)*	

Theme 10: Good Governance

Level 1	Level 2	*Level 3*
	Sub-theme: POLICY COHERENCE AND EFFECTIVENESS	
	1. New infringement cases, by policy area	2. *Transposition of Community law, by policy area*
	Sub-theme: OPENNESS AND PARTICIPATION	
	3. Voter turnout in national and EU parliamentary elections	4. *e-government on-line availability*
		5. *e-government usage by individuals*
	Sub-theme: ECONOMIC INSTRUMENTS	
	6. Shares of environmental and labour taxes in total tax revenues	
Contextual indicators	- *Level of citizens´ confidence in EU institutions (for sub-theme Policy coherence and effectiveness)*	

APPENDIX A.3: List of energy indicators for sustainable development (IAEA-International Atomic Energy Agency, 2005)

Social				
Theme	**Sub-theme**	**Energy indicator**		**Components**
Equity	Accessibility	SOC1	Share of households (or population) without electricity or commercial energy, or heavily dependent on non- commercial energy	-Households (or population) without electricity or commercial energy, or heavily dependent on non- commercial energy -Total number of households or population
	Affordability	SOC2	Share of household income spent on fuel and electricity	-Household income spent on fuel and electricity - Household income (total and poorest 20% of population)
	Disparities	SOC3	Household energy use for each income group and corresponding fuel mix	-Energy use per household for each income group (quintiles) -Household income for each income group (quintiles) -Corresponding fuel mix for each income group (quintiles)
Health	Safety	SOC4	Accident fatalities per energy produced by fuel chain	-Annual fatalities by fuel chain -Annual energy produced
Economic				
Theme	**Sub-theme**	**Energy indicator**		**Components**
Use and Production Patterns	Overall Use	ECO1	Energy use per capita	-Energy use (total primary energy supply, total final consumption and electricity use) -Total population
	Overall productivity	ECO2	Energy use per unit of GDP	-Energy use (total primary energy supply, total final consumption and electricity use) -GDP
	Supply efficiency	ECO3	Efficiency of energy conversion and distribution	-Losses in transformation systems including losses in electricity generation, transmission and distribution
	Production	ECO4	Reserves-to-production ratio	-Proven recoverable reserves -Total energy production
		ECO5	Resources-to-production ratio	-Total estimated resources -Total energy production
	End use	ECO6	Industrial energy intensities	-Energy use in industrial sector and by manufacturing branch -Corresponding value added
		ECO7	Agricultural energy intensities	-Energy use in agricultural sector -Corresponding value added
		ECO8	Service/ commercial energy intensities	-Energy use in service/ commercial sector -Corresponding value added
		ECO9	Household energy intensities	-Energy use in households and by key end use -Number of households, floor area, persons per household, appliance ownership
		ECO10	Transport energy intensities	-Energy use in passenger travel and freight sectors and by mode -Passenger-km travel and tonne-km freight and by mode

Economic				
Theme	**Sub-theme**	**Energy indicator**		**Components**
	Diversification (fuel mix)	ECO11	Fuel shares in energy and electricity	-Primary energy supply and final consumption, electricity generation and generating capacity by fuel type -Total primary energy supply, total final consumption, total electricity generation and total generating capacity
		ECO12	Non-carbon energy share in energy and electricity	-Primary supply, electricity generation and generating capacity by non-carbon energy -Total primary energy supply, total electricity generation and total generating capacity
		ECO13	Renewable energy share in energy and electricity	-Primary energy supply, final consumption and electricity generation and generating capacity by renewable energy -Total primary energy supply, total final consumption, total electricity generation and total generating capacity
	Prices	ECO14	End-use energy prices by fuel and by sector	-Energy prices (with and without tax/subsidy)
Security	Imports	ECO15	Net energy import dependency	-Energy imports -Total primary energy supply
	Strategic fuel stocks	ECO16	Stocks of critical fuels per corresponding fuel consumption	-Stocks of critical fuel (e.g. oil, gas, etc.) -Critical fuel consumption

Environmental				
Theme	**Sub-theme**	**Energy indicator**		**Components**
Atmosphere	Climate change	ENV1	GHG emissions from energy production and use per capita and per unit of GDP	-GHG emissions from energy production and use -Population and GDP
	Air quality	ENV2	Ambient concentrations of air pollutants in urban areas	-Concentrations of pollutants in air
		ENV3	Air pollutant emissions from energy systems	-Air pollutant emissions
Water	Water quality	ENV4	Contaminant discharges in liquid effluents from energy systems including oil discharges	-Contaminant discharges in liquid effluents
Land	Soil quality	ENV5	Soil area where acidi-fication exceeds critical load	-Affected soil area -Critical load
	Forest	ENV6	Rate of deforestation attributed to energy use	-Forest area at two different times -Biomass utilisation
	Solid waste generation and management	ENV7	Ratio of solid waste generation to units of energy produced	-Amount of solid waste -Energy produced
		ENV8	Ratio of solid waste properly disposed of total generated solid waste	-Amount of solid waste properly disposed of -Total amount of solid waste
		ENV9	Ratio of solid radioactive waste to units of energy produced	-Amount of radioactive waste (cumulative for a selected period of time) -Energy produced
		ENV10	Ratio of solid radioactive waste awaiting disposal to total generated solid radioactive waste	-Amount of radioactive waste awaiting disposal -Total volume of radioactive waste

APPENDIX A.4: Qualitative indicators applied in the evaluation of Energy and Fuel SCs

Indicator	Description
Economic	
Facility construction cost (€)	Construction cost of a facility/plant
Infrastructure cost (€)	Cost related to infrastructure development
Economic feasibility	The feasibility of the plant in economic terms in the considered time horizon
Investment / capital cost (€)	The fixed initial cost required for the total construction d the setup of the facility
Operational and Maintenance cost (€/year)	Cost related to the maintenance and operation of the plant i.e. personnel, energy, rent etc
Electricity Production cost (€/kWh)	Cost of electricity generated by different sources at the point of connection to a load or electricity grid
Specific Fuel cost (€/kWh)	Cost related to the specific fuel consumption of the plant
Levelised cost of electricity (LCOE) (€/kWh)	The average cost of producing electricity over the entire lifetime of the unit (it accounts for all investment, operation and maintenance, fuel, decommissioning and even CO_2 emissions costs)
Net Present Value (NPV) (€)	Measure of the profitability of the investment. It describes the difference between the present value of cash inflows and the present value of cash outflows.
Discounted Payback Time (DPBT)	DPBT represents the number of required years so that the cumulative discounted cash flows equate the initial investment;
Discounted Aggregate Cost Benefit	The DACB is the ratio between discounted economic benefits and costs
Internal Rate of Return (IRR) (%)	IRR is used in order to rank several prospective projects. It is used in capital budgeting for making the net present value of all cash flows from a particular project equal to zero.
PBP (years)	Payback period is the time in which the initial cash outflow of an investment is expected to be recovered from the cash inflows generated by the investment. It is one of the simplest investment appraisal techniques.
Profitability Index (PI)	The ratio of present value of future cash flows of a project to initial investment required for the project.
Technical / technological	
Technology transfer	The course transferring technological know-how (skill, technology experience etc)
Technological availability (qualitative)	How available and affordable is the technology
Infrastructure availability	The availability of the infrastructure
Production Capacity	The products that can be generated by a production plant or enterprise in a given period by using current resources
Reserves/Production ratio	The amount of a resource known to exist in an area and to be economically recoverable (proved reserves).
Maturity of technology	How mature is the technology
Affordability of technology	How affordable is the technology in economic terms
Peak load demand coverage	The ability to respond to peak demand and to insure overall grid stability in the long term in the context of a growing share of intermittent generation from some renewable energy sources
Land availability (ha)	Suitable, available land to be reserved for the specific / plant operation
Resources availability	Access to the available recourse for energy production
Technical / technological	
Capacity factor	A measure of the actual electricity produced over a period of time divided by the maximum theoretical electricity that could have been produced if the plant had been running at nameplate capacity
Energy availability	Amount of electricity provided from the technical system
Efficiency (of the energy conversion)	The efficiency with which input energy (e.g. chemical energy extracted from fuels) is transformed into useful output energy (i.e. electricity and useful heat)
Efficiency of energy conversion (%)	The technology's ability to convert the primary energy source to electricity
Energy Payback Time (EPBT),	EPBT is the time in which the energy input during the system life cycle is compensated by electricity generated by the system;
Energy Return on Investment (EROI),	EROI measures how much energy is gained after accounting for the energy required to produce a unit of the energy in question;
Greenhouse Gas Payback Time (GPBT),	GPBT is the time in which the GHG emissions during the system life cycle are compensated by GHG saved by alternative installation

Greenhouse Gas Return on Investment (GROI),	GROI indicates the GHG emissions saved for every unit of GHG emitted;
Environmental	
GHG emissions production (tn,kg)	The emissions produced by the plants tasks (either in tn of CO_2 equivalent or in specific type of emissions i.e. NOx, SO_2, etc)
Water consumption (tn)	The amount of water being consumed by the plants tasks
Waste production (tn/kWh)	The amount of waste being consumed by the plant per kWh produced
Net energy ratio (NER)	The NER is a ratio expressing the relationship between outside energy required to release useable energy and the useful energy itself.
CO_2 avoidance (kg/kWh)	The avoidance of CO_2 is a measure for the contribution to climate protection and thus reduces the greenhouse effect. CO_2 is emitted during the generation of electrical power as a result of burning fossil fuels (e.g. coal). Electricity which is generated using renewable energy (sun, wind, water, biomass, geothermal energy) does not produce (additional) CO_2.
LC impact of the technology	The impact of the technology in different impact categories (LCA includes all four stages of a product or process life cycle: raw material acquisition, manufacturing, use/reuse/maintenance, and recycle/waste management
External costs	Arise when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for, by the first group.
Land carbon dept	
Land utilisation	Land used over the entire lifecycle of the unit (e.g. fuel extraction, processing and delivery, construction, operation and decommissioning)
Land uses (m^2 per KW)	Amount of land use and degradation due to energy production and consumption considering life cycle
External costs (environmental)	Cost generated over the entire lifecycle of an electricity generation unit that are supported by entities other than the parties directly involved with the unit; this component refers to environmental costs (soil maintenance, clean-up of dust etc.)
Social	
Security of supply	Security of supply is given if ''consumer demand for electric energy is covered today and in the future in an uninterrupted and sustainable manner''
Fuel dependency (rate)	The rate of imported fossil based resources
Social acceptance	Public preference for the deployment or utilisation of a certain electricity generation technology
Social	
Gain of the local community	The gains of the local community by the development of new SCs or the improvement of existing energy SCs
Gain at country level	The gains of the country by the development of new or improved energy related SCs
Increase in quality of life	Increase of the wellbeing of the measured population
Social	
GDP contribution	The contribution of the new investments / or the improvement of the ESC in terms of GDP
Employment (rate)	The number of people being employed in the assorted ESCs
Decentralised energy production	The energy being produced at smaller/ decentralised plants
Accident risk	The risk of potential accident form the operation ot the ESC
External supply risk	The risk of supply shock incidence due to fuel imports
External cost (human health)	Cost that is generated over the entire lifecycle of an electricity generation unit which are supported by entities other than the parties directly involved with the unit; this component refers to human health costs (hospital and medication, loss of productivity etc.)
Job creation	"job-years" of full time employment created over the entire lifecycle of the unit
New job indicator	Number of paid hours per kWh produced in lifetime hours/kWh
Community economic indicator	Gain of GNP for the community per unit kWh
Local employment generation (Job per MW installed power)	Number of direct local employment opportunities created (considering mainly operation of the plant)

APPENDIX B: Data selection for model validation

Table 21: Values for the evaluation parameters with emphasis on Greece

Electricity generation plant	Efficiency	Capacity factor	Availability factor	Installation	Investment cost	Operation and maintenance costs	Variable costs	LCOE*	Elect. Cost	CO_2	Number of employees per unit of electricity	Water consumption	Area /land use
	(%)			(USD/kW)	(€/KWel)	(€/KWel/y)	€/MWhel)	($/MW h)*	(c/kWh)	($kgCO_2/kWh$)		(kg/ kWh_{el}) generated	(km^2/kW)
PV solar	10[1]/4-22[3]/1[4]	0.17[4]	0.99[4]	4500[1]	5000[5]	30[4]/9	0[4]	202.94-301.89[2]	75[1]/	0.1[1]/0.09[3]	0.87[2]	10[3]	0.12[1]/
Wind	28[1]/24-54[3]/1[4]	0.27[4]	0.98[4]	1100[1]	1100[4]/1150[5]	18[4]/13.5[5]	0[4]	76.28-109.61[2]	7[1]/	0.02[1]/0.025[3]		1[3]	0.79[1]/
Hydro	80[1]/>90[3]/1[4]	0.25[4]	0.98[4]	2000[1]	1300[4]/1850[5]	3[4]/49.5[5]	1.5[4]	26.35-46.66[2] (large)	8[1]/	0.04[1]/0.041[3]	0.27-0.55[2]	36[3]	0.13[1]/
Natural Gas	38[1]/45-53[3]/60[4]	0.85[4]	0.75[4]	650[1]	697[4]/350-1015[5]	18.8[4]/36.6-58.5[5]	1.6[4]	78.06-85.30[2]	4[1]/	0.38[1]/0.543[3]	0.11[2]	78[3]	0.04[1]/
Coal /Lignite	43[1]/32-45[3]/46[4]	0.85[4]	0.90[4]	1000[1]	1295[4]/1050-2090[5]	56.4[4]/38-90[5]	3.2[4]	64.37-79.36[2]	5.4[1]/	0.82[1]/1.004[3]	0.11[2]	78[3]	0.4[1]/
Oil	46[1]/ 45[4]	0.80[4]	0.85[4]		1150[4]/991[5]	38.0[4]/63.6	1.6[4]						

[1] (Afgan & Carvalho, 2002) / [2] (Maxim, 2014) / [3](Evans et al., 2009) / [4](Rentizelas & Georgakellos, 2014) / [5](Rafaj & Kypreos, 2007) in $
[*] LCOE—5% discount rate –10% discount rate

Values selected for the specific energy planning problem are listed in the Chapter 6.

Table 22: CO_2 emission factors in Life Cycle Analysis (in kg/MWh)

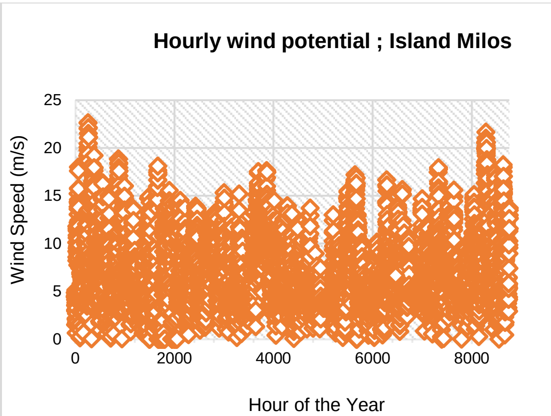
Life cycle stage	Lignite-fired power plants	Oil-fired power plants	Hydro power plants	Wind	PV	NG
Power plant construction	30.00[6]	1.65[6]	2.51[6]	8.20[6]	104[6]	1.81[6]
Lignite mining, processing & transportation, crude oil extraction & processing, refining	20.00[6]	62.58[6]	0[6]	0[6]	0[6]	4.88[6]
Power generation	1,230.00[6]	780.00[6]	0[6]	0[6]	0[6]	490.00[6]
Total from Georgakellos	1, 280.00[6]	844.23[6]	2.51[6]	8.20[6]	104[6]	496.69[6]
Total from Varun et al.	975.3[7]	742.1[7]		9.7–123.7[7]	53.4–250[7]	607.6[7]
[6](Georgakellos, 2012) [7](Varun et al., 2009)						

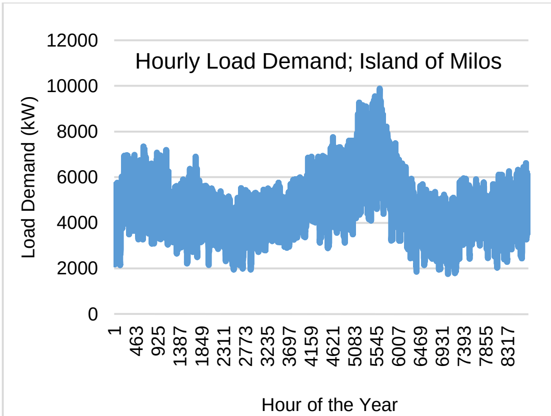
APPENDIX C: Single island cases

In this section preliminary relsuts from ESCs optimisation under the case of single islands (smaller consumers) modelled for Milos in Greece are listed (Papapostolou et al., 2014).

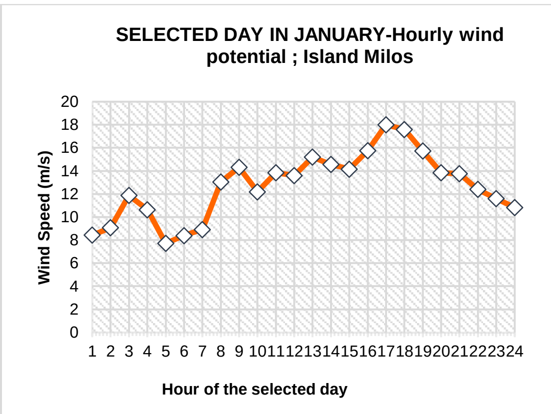
C1. Single island case: day-ahead optimisation for the island of Milos

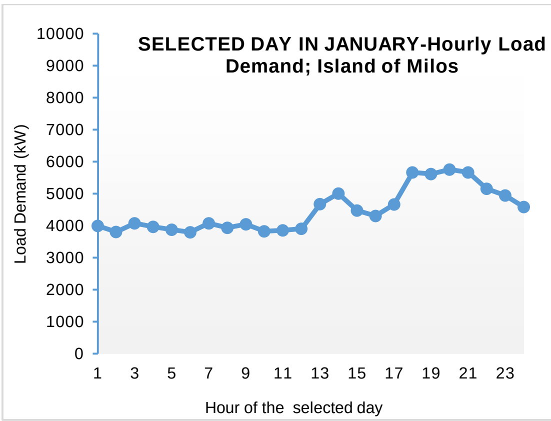
Milos, is positioned in the Cyclades island complex, and is characterised by a long with history on volcanism and a very good wind potential (Figure 87). In the existing power system of Milos, the electrical load is provided by thermal generators (diesel, heavy oil) and by wind power generation: peak load demand reaches 5 to 6 MW throughout the year, while in the tourist season the 10 MW and with the minimum demand ranging around 1.8 MW at low season and 4 MW at high season (Figures 88-92).





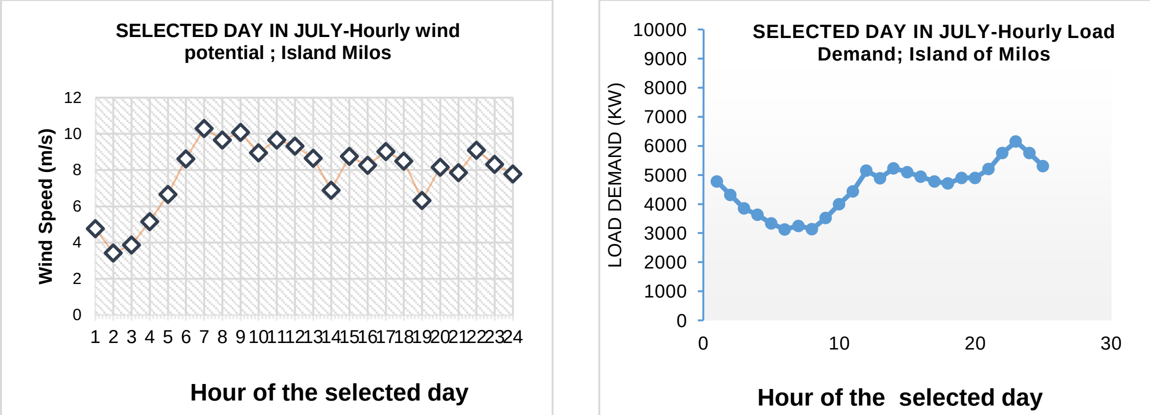
Figures 87, 88: Wind potential and load demand variation for Milos island (Data provided by HEDNO[6] for 2013)





Figures 89, 90: Wind potential and load demand variation for typical winter day in Milos (Data provided by HEDNO for 2013)

[6] Personal communication



Figures 91, 92: Wind potential and load demand variation for typical summer day in Milos (Data provided by HEDNO for 2013)

The model is implemented for a small but detailed time frame of one typical day in January for a wind–diesel energy SC configuration considering also an energy storage option consisting of a typical set of lead acid batteries. The diesel unit was treated as a base load power station, constant operating at or above its minimum capacity. The load variation was met by wind energy generation supplemented by storage operation in cases of energy deficit. Given the short time frame, it was possible to set up the model in the Excel Solver (Ch. 3.3.1). The data used for the model configuration are listed in Table 23.

Table 23: System characteristics and selected values for model optimisation (day-ahead-planning)

Parameter	Description	Value
$CAPrmax_{t,r}$	Maximum capacity of each electricity production plant r (MW)	Wind:10, Diesel: 2
$CAPrmin_{t,r}$	Minimum capacity of each electricity production plant r (MW)	Diesel: 1
$ESS\ min_{t,s}$, $ESS\ max_{t,s}$	Minimum and Maximum capacity of the storage station s (MWh)	Min: 1-Max: 10
$INVr_r$, $INVs_s$	Investment cost of the selected resource, storage station option (€/Kw or €/kWh)	Wind:1100, Diesel: 500, Energy storage: 200
MOr_r, MOs_s	Maintenance and operational cost of the selected resource, storage station (€/ kWh)	Wind: 0.02, Diesel: 0.03, Energy storage: 0.01
$LCREF$	Reference Life Cycle environmental footprint of selected ESC (in CO_2 eq / kWh)	Wind: 65
$LCENVFr_r$, $LCENVFs_s$	Life Cycle environmental footprint of each energy supply option (r,s,i) (in CO_2 eq / kWh)	Wind: 65, Diesel: 770, Energy storage: 275
$EMPLr_r$, $EMPLs_s$	Employment yield (€/ kWh)	Wind: 0.097, Diesel: 0.113, Energy storage: 0.030
LFr_r, LFs_s	Land footprint of each resource r,s capacity installation (in km^2 /kW)	Wind: 0.8, Diesel: 0.5, Energy storage: 0.6
$Amax$	Maximum land being available for the installation of each resource r,s (in km^2)	10% of the island area (160 km^2)
$EMFr_r$	Direct emission factor from each energy resource r (in kg CO_2 eq / kWh)	Wind: 0.0, Diesel: 0.8,
$GHGmax$	Emissions ceiling factor for the electricity generated (in kg CO_2 eq / kWh)	Natural gas: 0.4
PEX	Exchange losses from imported energy (and resources) (€/kWh)	0.078
PCO_2	Current commercialisation price of CO_2 (€/kWh),	15

The scalarisation of the set of objectives (techno-economic, environmental and social) is examined by applying weights' variation to evaluate their respective influence.

Optimisation results

In the first setup, equal emphasis is given on techno-economic and environmental implications of ESCs (α_1=0.4, α_2=0.4, and α_3=0.2). Strict air quality limitations are applied ($GHGmax$ =0.4) reassuring that in the final energy fuel mix, diesel contribution will be limited. Results, illustrated in Figure 93 which show the demand profile (blue line), wind generation (red line) and diesel power generation (green line), and in Figure 94, the demand profile and storage operation (balance). Under the initial dimensions set for the storage system ($ESS\ min_{t,s} = 1000kWh$) and diesel contribution ($CAPrmin_{t,r}$ =

1000kW) one may notice that in the time frame of 24 hours the model selects to treat the energy storage as backup system, loading it at its full capacity at the end of the day.

Also, one should underline that although wind is a more expensive resource, due mainly to its environmental performance and to emissions' limitations ceiling, is almost fully exploited to meet the demand and charge the energy storage system.

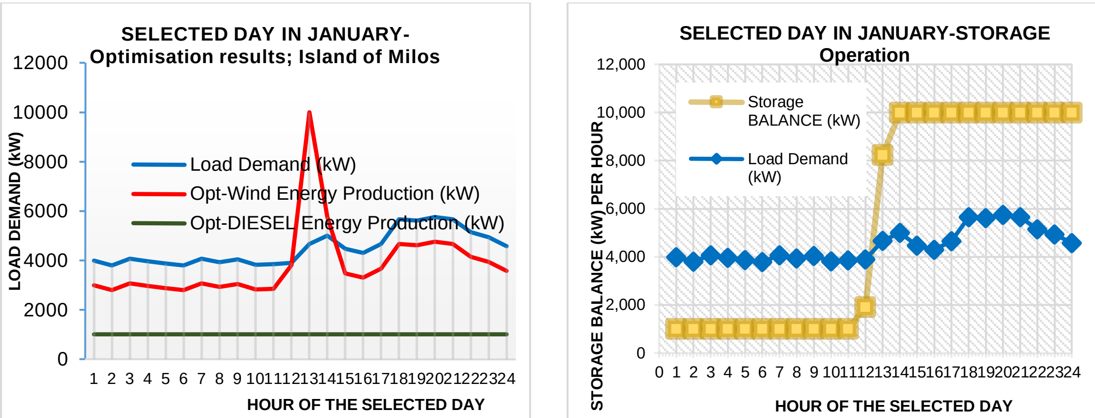


Figure 93, 94: Load demand profile, wind and diesel power generation and storage balance for the selected solution

In order to prove the sensitivity and the adaptability of the model to different optimisation strategies and goals, two alternative scenarios were considered: One with special emphasis in the environmental dimension of electricity generation –ignoring technical and social cost issues (α_1: 0.0, α_2: 1.0 α_3: 0.0) SC-1 -Figure 95, and a second, more moderate scenario which under the current techno-economic considerations, no emissions' ceiling is applicable for power production ($EMFr_r$ =0.8) (α_1: 1.0, α_2: 0.0, α_3: 0.0) Diesel power operation cost =0.02€/kWh - SC-2-Figure 96).

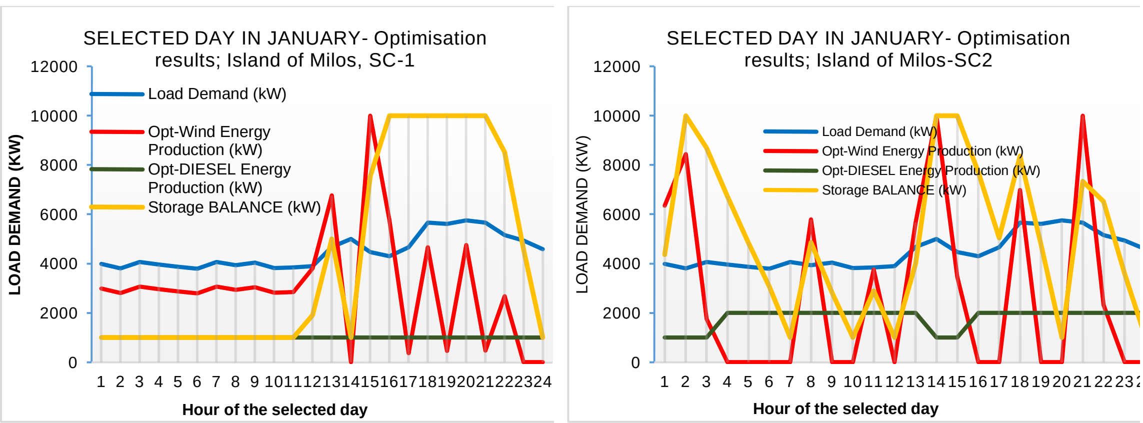


Figure 95, 96: Load demand profile, wind, diesel power generation and storage balance for the selected solutions

Results in the first case show that under mandates for air quality limitations with special focus on the environmental performance of energy systems, particularly in small – touristic attractive islands, RES-based plants are always the optimal solution, when constantly treated with an appropriately sized energy storage system. However, under the current techno-economic considerations with no provision of strict environmental standards and RES-penetration, diesel power stations will remain the preferable solution (Figure 96), exhausting their available per case capacity.

C2. Single island: Monthly based demand and energy supply optimisation characteristics

Model implementation is currently carried out for a typical load demand profile in a Greek island located in Cyclades complex, under the available energy supply options of wind, diesel and storage (Papapostolou et al., 2015). For load-demand profile data as well as wind potential for the specific case study, Milos time-series are used. In this case, diesel and storage act as base loads with minimum capacities 1000 kW per hour correspondingly whilst the remaining parameters are listed in Table 24. Demand has to be met a) in techno-economic terms by the combination of their optimal operation for a single day (always under the very discrete time step of one hour (Figure 97)) or b) just accounting for the maximum energy security (MaSOC) (Figure 98), or c) accounting both economic and Macro-Social implications (Figure 99) in a longer time period- one month.

Table 24: Parameters considered for model optimisation (single island case- monthly planning)

Parameter	Description	Value
$CAPrmax_{t,r}$	Maximum capacity of each electricity production plant r (MW)	Wind:10, Diesel: 10
$CAPrmin_{t,r}$	Minimum capacity of each electricity production plant r (MW)	Diesel: 1
$ESS\ max_{t,s}$	Maximum capacity of the storage station (MWh)	Energy storage: 10
$ESS\ min_{t,s}$	Minimum capacity of the storage station (MWh)	Energy storage: 1
MOr_r, MOs_s	Operational cost of the selected resource, storage station (€/ kWh)	Wind: -0.02, Diesel: -0.03, Energy storage: -0.01
$EMFr_r$	Direct emission factor from each energy resource r,s (in kg CO_2 eq / kWh)	Wind: 0.0, Diesel: 0.8, Energy storage: 0.0
$GHGmax$	Emissions ceiling factor for the electricity generated (in kg CO_2 eq / kWh)	1 (=Emissions generated by diesel x diesel =emission factor<= Electricity generated x1)
PEX	Exchange losses from imported energy (and resources) (€/kWh)	0.078
PCO_2	Current commercialisation price of CO_2 (€/kWh),	15

Optimisation results

Results concerning the operational characteristics of an existing (hypothetical) set of ESCs for a typical winter day and month, with low available energy production and for a corresponding winter month are illustrated in Figures 97-99. Optimisation is carried out for the specific time-frame in each case selected.

Results obtained evidence that different criteria under different set of priorities (weights) may result diverse ESCs configurations even in the limited planning horizon of one day. As one may notice in Figure 97, the model selects to maintain the energy storage level at its minimum capacity due to cost considerations, while in Figure 98, if the social implications are examined i.e. maximisation of energy security in the island, then storage is selected to operate periodically, eliminating in some instances diesel penetration. This can become more evident under a longer timeframe i.e. for one month for example, even if equally applying techno-economic and social criteria to the optimisation of the energy planning problem (α_1=0.5, α_2=0, α_3=0.5). As illustrated in Figure 99, storage contributes significantly, and during some days is kept at its full load. Diesel and wind production is periodically switching according to resources' availability (wind potential) and to the cost function applied for electricity production. In addition, if considering the long term aspect of energy planning -especially in large scale / state level problems- the security of energy supply maybe of greater importance than the minimisation of the total operational cost of the existing energy production plants. However according to the proposed modelling approach cited in the present work a temporal and local optimum may be obtained according to the location specific criteria set, in each case study under examination.

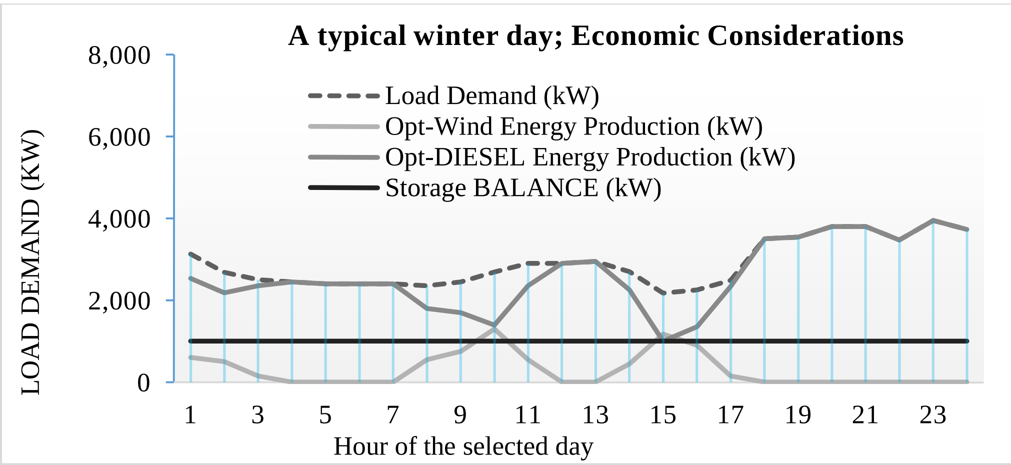


Figure 97: Optimisation results- daily load- Economic Considerations (α_1=1, α_2=0, α_3=0)

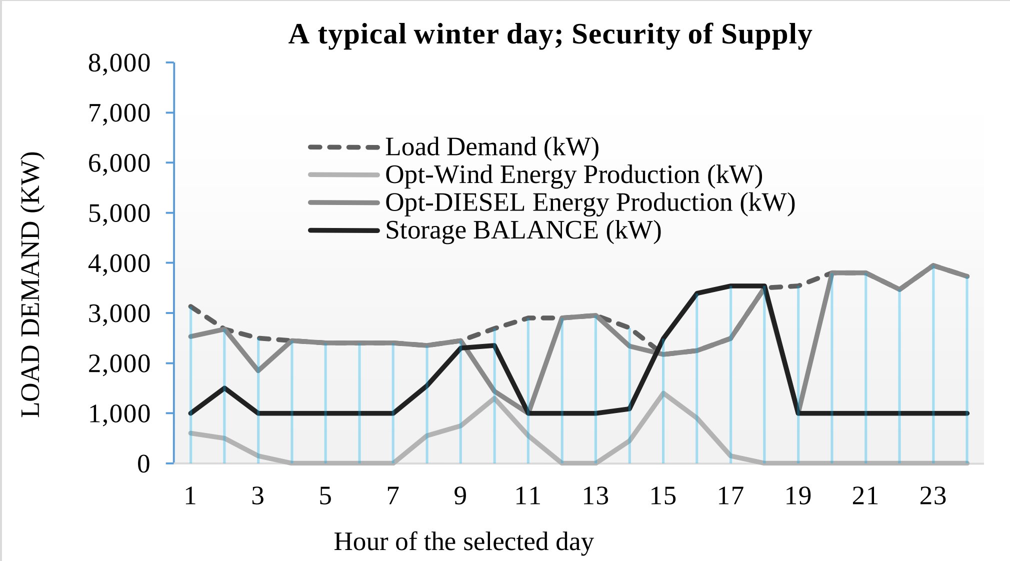


Figure 98: Optimisation results- daily load- Social/ Security of Supply Considerations (α_1=0, α_2=0, α_3=1)

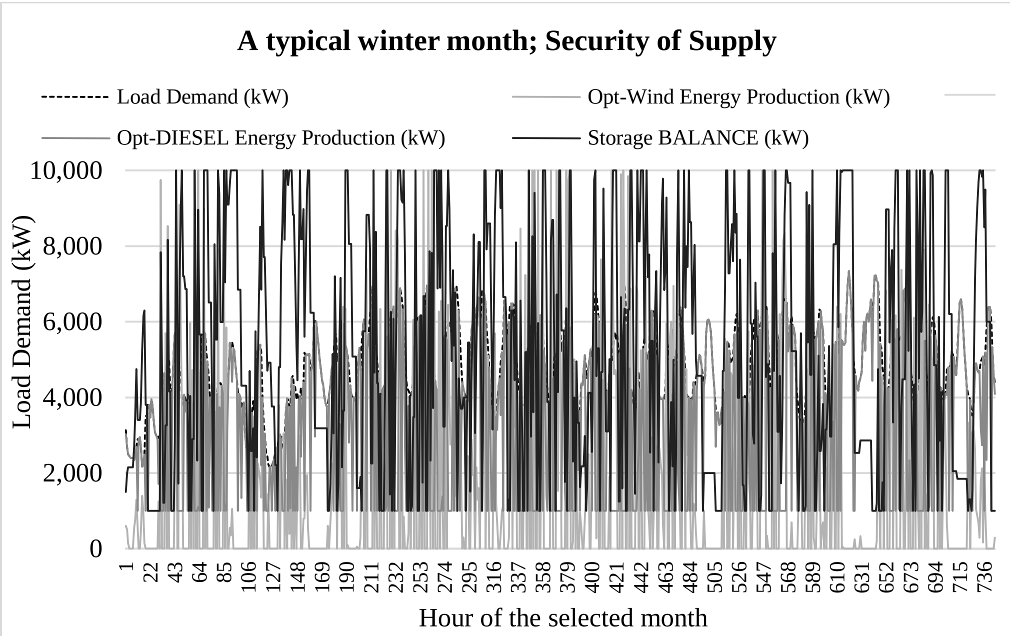


Figure 99: Optimisation results- monthly load- Economic and Macro-Social Considerations (α_1=0.5, α_2=0, α_3=0.5)

APPENDIX D: GAMS computational code

APPENDIX D1: Operational model

```
*===Social, Environmental and Economic Impacts of Alternative Energy
and Fuel Supply Chains
*===Papapostolou Christiana
*===Operational model -evaluation of the existing situation (Non-
storage consideration)

SETS
t   time sequence / 1*8760/
r   Resourses / diesel,wind, PV/
s   storage / storage /
i   interconnection / interconnection /
u   demand / demand /;

PARAMETERS
a1 /0.333/,
a2 /0.333/,
a3 /0.333/ ;

parameter v(t,u) demand per hour ;
$CALL GDXXRW.EXE CP_DEC15_Operational_model_NON-storage.xlsx par=v
rng=Indata!C2:D10000
$GDXIN CP_DEC15_Operational_model_NON-storage.gdx
$LOAD v
$GDXIN

parameter capminr(t,r) resources min capacity ;
$CALL GDXXRW.EXE CP_DEC15_Operational_model_NON-storage.xlsx
par=capminr rng=Indata!C2:H10000
$GDXIN CP_DEC15_Operational_model_NON-storage.gdx
$LOAD capminr
$GDXIN


parameter capmaxr(t,r) resources max capacity ;
$CALL GDXXRW.EXE CP_DEC15_Operational_model_NON-storage.xlsx
par=capmaxr rng=Indata!I2:M10000
$GDXIN CP_DEC15_Operational_model_NON-storage.gdx
$LOAD capmaxr
$GDXIN


PARAMETERS
*===ECONOMIC PARAMETERS
*===CP_DEC15_Investment-wind    1100  -    PV  1200 - diesel  850 /
storage 650/
INVr(r) Investment cost of each resource annualised values for 15
years(€ per kW)
/wind    0
 PV      0
 diesel  0 /
INVs(s) Investment cost of each storage station (€ per kWh)
/ storage 0/
INVi(i) Investment cost of each interconnection option (€ per kW)
/ interconnection 0/
INVsg(s)  Investment cost of each storage generator (€ per kW)
/ storage 0/
INVsp(s)  Investment cost of each storage "pumping" (€ per kW)
/ storage 0/
```

```
MOr(r)   Maintenance and operational variable cost of each resource
(in the case of diesel the fuel cost consumption is included as
well(€ per kWh)
*===diesel generator size aprox. 1000kW fuel consumption at 3/4 Load
198 lt/h, heating diesel fuel price 0.8€/lt -->
/wind      0.0
 PV        0.0
 diesel    0.16/
MOs(s)   Maintenance and operational variable cost of each storage
station (€ per kWh)
/ storage  0.0 /
MOi(i)   Maintenance and operational variable cost of each
interconnection option (€ per kWh)
/ interconnection 0.0 /


FCr(r)   Fixed annual cost of each resource (€ per kW)
*===wind=1-4% of the investment cost  - value selected 1%
*===PV=1% of the investment cost   - value selected 1%
*===diesel=4-8% of the investment cost   -  value selected 4%
*===storage=2-5% of the investment cost  -  value selected 2%

/wind      0.0
 PV        0.0
 diesel    0.0/
FCs(s)   Fixed annual cost of each storage station (€ per kWh)
/ storage  0.0 /
FCi(i)   Fixed annual cost of each interconnection option (€ per
kWh)
/ interconnection  0.0 /
FCsg(s)   Fixed annual cost of electricity generated at the storage
station s (€ per kW)
/ storage 0.0 /
FCsp(s)   Fixed annual cost of electricity (pumped) at the storage
station (€ per kW)
/ storage 0.0 /


*===ENVIRONMENTAL PARAMETERS
LCENVFr(r) Life Cycle environmental footprint of the selected
resource (kg CO2 eq per kWh)
/ wind     0.065
  PV       0.150
  diesel   0.770/
LCENVFs(s) Life Cycle environmental footprint of the storage station
(kg CO2 eq per kWh)
/ storage  0.275 /
LCENVFi(i) Life Cycle environmental footprint of the interconnection
option (kg CO2 eq per kWh)
/ interconnection  0.0 /

EMFr(r) Direct emission factor from each energy resource (kg CO2 eq
per kWh)
/ wind   0.0
  PV     0.0
  diesel 0.8 /
LFr(r) Land footprint of each resource plant (km2 per kW)
/ wind   0.0079
  PV     0.0012
  diesel 0.00000064 /
LFs(s) Land footprint of each storage station plant (km2 per kWh)
/ storage 0.00000002 /
```

```
*===SOCIAL PARAMETERS
EMPLr(r) Employment yield of each resource (€ per kWh)
/ wind 0.00099
PV     0.00118
diesel 0.00148    /
EMPLs(s) Employment yield of each storage station (€ per kWh)
/ storage 0.000099  /
EMPLi(i) Employment yield of each interconnection option (€ per kWh)
/ interconnection 0.0  /
SECr(r)  Energy security index for each resource
/ wind  0
  PV    0
diesel -1 /
SECs(s)  Energy security index for each storage station
/ storage 1 /
SECi(i)  Energy security index for each interconnection option
/ interconnection -1 /


SCALARS
Amax   Maximum land being available for the installation in km2
/1000/
PEL    Current commercialization price of electricity generated (€
per kWh) /0.14/
PEL2   Current commercialization price of electricity "purchased
from the storage stations" /0.14/
PEL3   Current commercialization price of electricity "purchased
from the interconnection option"  /0.14/
PCO2   Current commercialization price of CO2 (€ to kg) /0.015 /
PEX    Exchange losses from imported energy (and resources) (€ per
kWh) /0.078/
LCREF  Reference Life Cycle environmental footprint of selected ESC
(kg CO2 eq per kWh)/0.065/
np     Storage "pumping" stations charging coefficient /0.9/
ng     Storage generators discharging coefficient /0.9/
nch    Pumpimg - generation coefficient /0.25/
ESSmin Minimum operational capacity of storage station s (kWh)/ 0/
Essmax Maximum operational capacity of storage station s (kWh)/0/
*GHGmax Greenhouse Gas emissions reduction coefficient  /0.8/
INTmax Maximum capacity of interconnection option   /0/
INTmin Minimum capacity of interconnection option   /0/     ;


VARIABLES
EGr(t,r)  Energy generation from thermal resources r at time-step t
(kWh)
ESg(t,s)  Energy being generated by storage station at time-step t
(kWh)
ESs(t,s)  Energy being stored at storage station generated from
resources r at time-step t (kWh)
ESl(t,s)  Energy storage level
EIN(t,i)  Energy being imported or exported from the interconnection
option i at time-step t (kWh)
Pr(r)     Nominal capacity of electricity generation plants r (kW)
Ps(s)     Nominal capacity of storage stations  s(kWh)
Pi(i)     Nominal capacity of interconnection option i(kW)
Psg(s)    Nominal capacity of the generator (kW)
Psp(s)    Nominal capacity of the "pumpming system" (kW)
Z         Total benefit from ESC configuration (€)
ECONV     Economical value
ENVV      Environmental value
SOCV      Social value ;
```

```
POSITIVE VARIABLES  EGr(t,r),ESl(t,s), EIN(t,i),ESg(t,s), ESs(t,s),
Psg(s),Psp(s) ;

EQUATIONS
VALUEECO            Economical value
VALUEENV            Environmental value
VALUESOC            Social value
BENEFIT             Define objective function

CONSmaxr(t,r)       Constraint  maximum capacity for resource r
CONSmaxs(t,s)       Constraint  maximum capacity for energy storage
generation
CONSmaxl(t,s)       Constraint  maximum capacity for energy storage
level
CONSmaxi(t,i)       Constraint  maximum capacity for interconnection
option i

CONSminr(t,r)       Constraint  minimum capacity for resource r
CONSmins(t,s)       Constraint  minimum capacity for energy storage
pumping
CONSminl(t,s)       Constraint  minimum capacity for energy storage
pumping
CONSmini(t,i)       Constraint  minimum capacity for interconnection
option i

ESSL(t,s,u)         Energy storage level
SPump(s)            Sizing of the pumping
SGen(s)             Sizing of the generator
DEM(t,s,i,u)          Constrain of demand u for time-step t   ;
*DIREMI(r,t,u)       Direct emissions (in CO2eq) from each energy
supply resource for the selected Horizon H  ;

VALUEECO          ..  ECONV =E= sum((t,r), EGr(t,r)*PEL)+ sum((t,s),
ESg(t,s)*PEL)+ sum((t,i), EIN(t,i)*PEL)- sum((t,s), ESs(t,s)*PEL2)-
sum((t,i), EIN(t,i)*PEL3)-sum(r,INVr(r)*Pr(r)) -
sum(s,INVs(s)*Ps(s))- sum(s,INVsg(s)*Psg(s))  -
sum(s,INVsp(s)*Psp(s))- sum(i,INVi(i)*Pi(i))- sum(r, FCr(r)*Pr(r)) -
sum(i, FCi(i)*Pi(i))- sum(s, FCs(s)*Ps(s)) - sum(s, FCsg(s)*Psg(s))-
sum(s, FCsp(s)*Psp(s))-sum((t,r), EGr(t,r)*MOr(r))    - sum((t,s),
ESs(t,s)*MOs(s)) - sum((t,s), ESg(t,s)*MOs(s))  - sum((t,i),
EIN(t,i)*MOi(i));

VALUEENV          ..  ENVV =E= sum((t,r), (EGr(t,r)*(LCREF-
LCENVFr(r)))*PCO2)+sum((t,s),(ESg(t,s)*(LCREF-
LCENVFs(s)))*PCO2)+sum((t,i),(EIN(t,i)*(LCREF-LCENVFi(i)))*PCO2);

VALUESOC          ..  SOCV =E= sum((t,r),((EMPLr(r)+(SECr(r)*PEX))*
EGr(t,r)))+ sum((t,s),((EMPLs(s)+(SECs(s)*PEX))*ESg(t,s)))+
sum((t,i),((EMPLi(i)+(SECi(i)*PEX))*EIN(t,i)));

BENEFIT              ..  Z =E= a1*ECONV+ a2*ENVV + a3*SOCV;

*===Energy resources capacity constraint

CONSmaxr(t,r)     ..  EGr(t,r) =L= capmaxr(t,r);
CONSminr(t,r)     ..  EGr(t,r) =G= capminr(t,r);

*===Energy storage capacity constraint in generation and pumping

CONSmaxs(t,s)     ..  ESg(t,s) =L= ng *Psg(s);
CONSmins(t,s)     ..  ESs(t,s) =L= np *Psp(s);

*===Energy storage level constraint
CONSmaxl(t,s)     ..  ESl(t,s) =L= ESSmax;
```

```
CONSminl(t,s)     ..  ESl(t,s) =G= ESSmin;

*===Interconnection option capacity constraints

CONSmaxi(t,i)     ..  EIN(t,i) =L= INTmax;
CONSmini(t,i)     ..  EIN(t,i) =G= INTmin;


ESSL(t,s,u)        ..  ESl(t,s)=e= ESl(t-1,s)-
(1/ng)*ESg(t,s)+np*(ESs(t,s)) ;

SPump(s)          .. Psp(s)=e=nch*ESSmax;

SGen(s)           .. Psg(s)=e=nch*ESSmax;

DEM(t,s,i,u)        ..  sum(r,EGr(t,r)) + ESg(t,s)-ESs(t,s)+EIN(t,i)
=e=  v(t,u);

*DIREMI(r,t,u)     ..  EGr(t,r)*EMFr(r)=l= GHGmax*v(t,u) ;


MODEL ENERGY /ALL/ ;
OPTION iterlim = 1000000000 ;
SOLVE ENERGY USING LP maximizing Z ;

ESs.l(t,s)$(not ESs.l(t,s)) = eps;
ESg.l(t,s)$(not ESg.l(t,s)) = eps;
ESl.l(t,s)$(not ESl.l(t,s)) = eps;

*=== Export to Excel using GDX utilities
*=== First unload to GDX file (occurs during execution phase)
execute_unload "CP_DEC15_Operational_model_NON-storage.gdx" EGr.l,
ESs.l, EIN.l, ESl.l,ESg.l, Z.l, ECONV.l,ENVV.l,SOCV.l ;


*=== Now write to variable levels to Excel file from GDX

execute 'gdxxrw.exe CP_DEC15_Operational_model_NON-storage.gdx
var=EGr.L rng=ResultsInv!A1:D10000 trace=0';
execute 'gdxxrw.exe CP_DEC15_Operational_model_NON-storage.gdx
var=ESs.L rng=Results_energy-storage!a2:b10000 trace=0';
execute 'gdxxrw.exe CP_DEC15_Operational_model_NON-storage.gdx
var=ESl.L rng=Results_energy-storage!c2:d10000 trace=0';
execute 'gdxxrw.exe CP_DEC15_Operational_model_NON-storage.gdx
var=ESg.L rng=Results_energy-storage!e2:f10000 trace=0';
*=== Write marginals to a different sheet with a specific range

execute 'gdxxrw.exe CP_DEC15_Operational_model_NON-storage.gdx
var=Z.L rng=ResultsInv!H2';

execute 'gdxxrw.exe CP_DEC15_Operational_model_NON-storage.gdx
var=ECONV.L rng=ResultsInv!H4';
execute 'gdxxrw.exe CP_DEC15_Operational_model_NON-storage.gdx
var=ENVV.L rng=ResultsInv!H5';
execute 'gdxxrw.exe CP_DEC15_Operational_model_NON-storage.gdx
var=SOCV.L rng=ResultsInv!H6';
```

APPENDIX D2: Operational model with binary constrains

```
*===Social, Environmental and Economic Impacts of Alternative Energy
and Fuel Supply Chains
*===Papapostolou Christiana
*===Operational model with the consideration of multiple resources
and storage
*===Binary selection over one resource r at each time-step t

SETS
t   time sequence / 1*8760/
r   Resourses / diesel,wind, PV/
s   storage / storage /
i   interconnection / interconnection /
u   demand / demand /;

PARAMETERS
a1 /0.333/,
a2 /0.333/,
a3 /0.333/ ;

parameter v(t,u) demand per hour ;
$CALL GDXXRW.EXE CP_DEC15_Operational_model_storage_binary.xlsx
par=v rng=Indata!C2:D10000
$GDXIN CP_DEC15_Operational_model_storage_binary.gdx
$LOAD v
$GDXIN

parameter capminr(t,r) resources min capacity ;
$CALL GDXXRW.EXE CP_DEC15_Operational_model_storage_binary.xlsx
par=capminr rng=Indata!C2:H10000
$GDXIN CP_DEC15_Operational_model_storage_binary.gdx
$LOAD capminr
$GDXIN

parameter capmaxr(t,r) resources max capacity ;
$CALL GDXXRW.EXE CP_DEC15_Operational_model_storage_binary.xlsx
par=capmaxr rng=Indata!I2:M10000
$GDXIN CP_DEC15_Operational_model_storage_binary.gdx
$LOAD capmaxr
$GDXIN

PARAMETERS
*===ECONOMIC PARAMETERS
*===CP_DEC15_Investment-wind    1100   -    PV      1200 - diesel
850 -  storage 650
INVr(r) Investment cost of each resource annualised for 15 years(€
per kW)
/wind    0
 PV      0
 diesel  0 /
INVs(s) Investment cost of each storage station (€ per kWh)
/ storage 0/
INVi(i) Investment cost of each interconnection option (€ per kW)
/ interconnection 0/
INVsg(s)  Investment cost of each storage generator (€ per kW)
/ storage 0/
INVsp(s)  Investment cost of each storage "pumping" (€ per kW)
/ storage 0/
```

```
MOr(r)   Maintenance and operational variable cost of each resource
(in the case of diesel the fuel cost consumption is included as
well(€ per kWh)

*===diesel generator size aprox. 1000kW fuel consumption at 3/4 Load
198 lt/h, heating diesel fuel price 0.8€/lt -->
/wind       0.18
 PV         0.0
 diesel     0.16/
MOs(s)   Maintenance and operational variable cost of each storage
station (€ per kWh)
/ storage  0.0 /
MOi(i)   Maintenance and operational variable cost of each
interconnection option (€ per kWh)
/ interconnection 0.0 /

FCr(r)   Fixed annual cost of each resource (€ per kW)
*===wind=1-4% of the investment cost  - value selected 1%
*===PV=1% of the investment cost   - value selected 1%
*===diesel=4-8% of the investment cost   -  value selected 4%
*===storage=2-5% of the investment cost  -  value selected 2%

/wind       0.0
 PV         0.0
 diesel     0.0/
FCs(s)   Fixed annual cost of each storage station (€ per kWh)
/ storage  0.0 /
FCi(i)   Fixed annual cost of each interconnection option (€ per
kWh)
/ interconnection  0.0 /
FCsg(s)   Fixed annual cost of electricity generated at the storage
station s (€ per kW)
/ storage 0.0 /
FCsp(s)   Fixed annual cost of electricity (pumped) at the storage
station (€ per kW)
/ storage 0.0 /


*===ENVIRONMENTAL PARAMETERS
LCENVFr(r) Life Cycle environmental footprint of the selected
resource (kg CO2 eq per kWh)
/ wind      0.065
  PV        0.150
  diesel    0.770/
LCENVFs(s) Life Cycle environmental footprint of the storage station
(kg CO2 eq per kWh)
/ storage  0.275 /
LCENVFi(i) Life Cycle environmental footprint of the interconnection
option (kg CO2 eq per kWh)
/ interconnection  0.0 /

EMFr(r) Direct emission factor from each energy resource (kg CO2 eq
per kWh)
/ wind   0.0
  PV     0.0
  diesel 0.8 /

LFr(r) Land footprint of each resource plant (km2 per kW)
/ wind   0.0079
  PV     0.0012
  diesel 0.00000064 /
LFs(s) Land footprint of each storage station plant (km2 per kWh)
/ storage 0.00000002 /
```

```
*===SOCIAL PARAMETERS
EMPLr(r) Employment yield of each resource (€ per kWh)
/ wind 0.00099
PV     0.00118
diesel 0.00148    /
EMPLs(s) Employment yield of each storage station (€ per kWh)
/ storage 0.000099  /
EMPLi(i) Employment yield of each interconnection option (€ per kWh)
/ interconnection 0.0  /
SECr(r)  Energy security index for each resource
/ wind  0
  PV    0
diesel -1 /
SECs(s)  Energy security index for each storage station
/ storage 1 /
SECi(i)  Energy security index for each interconnection option
/ interconnection -1 /

SCALARS
Amax Maximum land being available for the installation in km2 /1000/
PEL  Current commercialization price of electricity generated (€ per
kWh) /0.14/
PEL2 Current commercialization price of electricity "purchased from
the storage stations" /0.14/
PEL3   Current commercialization price of electricity "purchased
from the interconnection option"  /0.14/
PCO2 Current commercialization price of CO2 (€ to kg) /0.015 /
PEX  Exchange losses from imported energy (and resources) (€ per
kWh) /0.078/
LCREF Reference Life Cycle environmental footprint of selected ESC
(kg CO2 eq per kWh)/0.065/
np  Storage "pumping" stations charging coefficient /0.9/
ng  Storage generators discharging coefficient /0.9/
nch     Pumpimg - generation coefficient /0.25/
ESSmin / 0/
Essmax/150000/
GHGmax Maximum -quality coefficient - for emission permits /0.8/
INTmax Maximum capacity of interconnection option   /0/
INTmin  Minimum capacity of interconnection option   /0/     ;


VARIABLES
EGr(t,r) Energy generation from resources r at time-step t (kWh)
ESg(t,s) Energy being generated by storage station at time-step t
(kWh)
ESs(t,s) Energy being stored at storage station generated at time-
step t (kWh)
EIN(t,i) Energy being imported or exported from the interconnection
option i at time-step t (kWh)
ESl(t,s) Energy storage level
Pr(r)    Nominal capacity of electricity generation plants r (kW)
Ps(s)    Nominal capacity of storage stations  s(kWh)
Pi(i)    Nominal capacity of interconnection option i(kW)
Psg(s)   Nominal capacity of the generator (kW)
Psp(s)   Nominal capacity of the "pumpming system" (kW)
Z        Total benefit from ESC configuration (€)
ECONV    Economical value
ENVV     Environmental value
SOCV     Social value
Br(t,r)  Decision binary variable for each resourse r;
```

```
POSITIVE VARIABLES  EGr(t,r),ESl(t,s), EIN(t,i),ESg(t,s), ESs(t,s),
Psg(s),Psp(s) ;
BINARY VARIABLE Br(t,r);

EQUATIONS
VALUEECO            Economical value
VALUEENV            Environmental value
VALUESOC            Social value
BENEFIT             Define objective function
CONSmaxr(t,r)       Constraint  maximum capacity for resource r
CONSmaxs(t,s)       Constraint  maximum capacity for energy storage
generation
CONSmaxl(t,s)       Constraint  maximum capacity for energy storage
level
CONSmaxi(t,i)       Constraint  maximum capacity for interconnection
option i
CONSminr(t,r)       Constraint  minimum capacity for resource r
CONSmins(t,s)       Constraint  minimum capacity for energy storage
pumping
CONSminl(t,s)       Constraint  minimum capacity for energy storage
pumping
CONSmini(t,i)       Constraint  minimum capacity for interconnection
option i

ESSL(t,s,u)         Energy storage level
SPump(s)            Sizing of the pumping
SGen(s)             Sizing of the generator
DEM(t,s,i,u)        Constrain of demand u for time-step t
DIREMI(r,t,u)       Direct emissions (in CO2eq) from each energy
supply resource for the selected Horizon H
lim(t)              Limit selection of resources r in each time step
t to one;

VALUEECO          ..  ECONV =E= sum((t,r), EGr(t,r)*PEL)+ sum((t,s),
ESg(t,s)*PEL)+ sum((t,i), EIN(t,i)*PEL)- sum((t,s), ESs(t,s)*PEL2)-
sum((t,i), EIN(t,i)*PEL3)-sum(r,INVr(r)*Pr(r)) -
sum(s,INVs(s)*Ps(s))- sum(s,INVsg(s)*Psg(s))  -
sum(s,INVsp(s)*Psp(s))- sum(i,INVi(i)*Pi(i))- sum(r, FCr(r)*Pr(r)) -
sum(i, FCi(i)*Pi(i))- sum(s, FCs(s)*Ps(s)) - sum(s, FCsg(s)*Psg(s))-
sum(s, FCsp(s)*Psp(s))-sum((t,r), EGr(t,r)*MOr(r))    - sum((t,s),
ESs(t,s)*MOs(s)) - sum((t,s), ESg(t,s)*MOs(s))  - sum((t,i),
EIN(t,i)*MOi(i));


VALUEENV          ..  ENVV =E= sum((t,r), (EGr(t,r)*(LCREF-
LCENVFr(r)))*PCO2)+sum((t,s),(ESg(t,s)*(LCREF-
LCENVFs(s)))*PCO2)+sum((t,i),(EIN(t,i)*(LCREF-LCENVFi(i)))*PCO2);

VALUESOC          ..  SOCV =E= sum((t,r),((EMPLr(r)+(SECr(r)*PEX))*
EGr(t,r)))+ sum((t,s),((EMPLs(s)+(SECs(s)*PEX))*ESg(t,s)))+
sum((t,i),((EMPLi(i)+(SECi(i)*PEX))*EIN(t,i)));

BENEFIT              ..  Z =E= a1*ECONV+ a2*ENVV + a3*SOCV;

*===Energy resources capacity constraint

CONSmaxr(t,r)     ..  EGr(t,r) =L= capmaxr(t,r)*Br(t,r);
CONSminr(t,r)     ..  EGr(t,r) =G= capminr(t,r)*Br(t,r);

*===Energy storage capacity constraint in generation and pumping

CONSmaxs(t,s)     ..  ESg(t,s) =L= ng *Psg(s);
CONSmins(t,s)     ..  ESs(t,s) =L= np *Psp(s);
```

```
*===Energy storage level constraint

CONSmaxl(t,s)     ..  ESl(t,s) =L= ESSmax;
CONSminl(t,s)     ..  ESl(t,s) =G= ESSmin;

*===Interconnection option capacity constraints

CONSmaxi(t,i)     ..  EIN(t,i) =L= INTmax;
CONSmini(t,i)     ..  EIN(t,i) =G= INTmin;


ESSL(t,s,u)        ..  ESl(t,s)=e= ESl(t-1,s)-
(1/ng)*ESg(t,s)+np*(ESs(t,s)) ;

SPump(s)          .. Psp(s)=e=nch*ESSmax;

SGen(s)           .. Psg(s)=e=nch*ESSmax;

DEM(t,s,i,u)      ..  sum(r,EGr(t,r)) + ESg(t,s)-ESs(t,s)+EIN(t,i)
=e=  v(t,u);

DIREMI(r,t,u)     ..  EGr(t,r)*EMFr(r)=l= GHGmax*v(t,u) ;

* only one choice for resources plants' operation is feasible
lim(t)         ..sum(r,Br(t,r))=e=1;

MODEL ENERGY /ALL/ ;
OPTION iterlim = 1000000000 ;
SOLVE ENERGY USING MIP maximizing Z ;

ESs.l(t,s)$(not ESs.l(t,s)) = eps;
ESg.l(t,s)$(not ESg.l(t,s)) = eps;
ESl.l(t,s)$(not ESl.l(t,s)) = eps;

*=== Export to Excel using GDX utilities
*=== First unload to GDX file (occurs during execution phase)
execute_unload "CP_DEC15_Operational_model_storage_binary.gdx"
EGr.l, ESs.l, EIN.l, ESl.l,ESg.l, Z.l, ECONV.l,ENVV.l,SOCV.l ;


*=== Now write to variable levels to Excel file from GDX

execute 'gdxxrw.exe CP_DEC15_Operational_model_storage_binary.gdx
var=EGr.L rng=ResultsInv!A1:D10000 trace=0';
execute 'gdxxrw.exe CP_DEC15_Operational_model_storage_binary.gdx
var=ESs.L rng=Results_energy-storage!a2:b10000 trace=0';
execute 'gdxxrw.exe CP_DEC15_Operational_model_storage_binary.gdx
var=ESl.L rng=Results_energy-storage!c2:d10000 trace=0';
execute 'gdxxrw.exe CP_DEC15_Operational_model_storage_binary.gdx
var=ESg.L rng=Results_energy-storage!e2:f10000 trace=0';
*=== Write marginals to a different sheet with a specific range

execute 'gdxxrw.exe CP_DEC15_Operational_model_storage_binary.gdx
var=Z.L rng=ResultsInv!H2';

execute 'gdxxrw.exe CP_DEC15_Operational_model_storage_binary.gdx
var=ECONV.L rng=ResultsInv!H4';
execute 'gdxxrw.exe CP_DEC15_Operational_model_storage_binary.gdx
var=ENVV.L rng=ResultsInv!H5';
execute 'gdxxrw.exe CP_DEC15_Operational_model_storage_binary.gdx
var=SOCV.L rng=ResultsInv!H6';
```

APPENDIX D3: Investment model

```
*===Social, Environmental and Economic Impacts of Alternative Energy
and Fuel Supply Chains
*===Papapostolou Christiana
*===Investment model with the consideration of multiple resources
capacities and energy storage

SETS
t   time sequence / 1*8760/
r   Resources / diesel, wind, PV/
s   storage / storage /
i   interconnection / interconnection /
u   demand / demand /;

PARAMETERS
a1 /0.333/,
a2 /0.333/,
a3 /0.333/ ;

parameter v(t,u) demand profile per hour ;
$CALL GDXXRW.EXE CP_DEC15_Investment_model_all.xlsx par=v
rng=Indata!A2:B10000
$GDXIN CP_DEC15_Investment_model_all.gdx
$LOAD v
$GDXIN

parameter CFmaxr(t,r) resources max capacity factor constrain ;
$CALL GDXXRW.EXE CP_DEC15_Investment_model_all.xlsx par=CFmaxr
rng=Indata!A2:F10000
$GDXIN CP_DEC15_Investment_model_all.gdx
$LOAD CFmaxr
$GDXIN

parameter CFminr(t,r) resources min capacity factor constrain ;
$CALL GDXXRW.EXE CP_DEC15_Investment_model_all.xlsx par=CFminr
rng=Indata!G2:K100
$GDXIN CP_DEC15_Investment_model_all.gdx
$LOAD CFminr
$GDXIN


PARAMETERS
*===ECONOMIC PARAMETERS
*===06115_Investment-wind 1100 -PV 1200 –diesel 850 -storage 650
INVr(r) Investment cost of each resource annualised for 15 years (€
per kW)
/wind    73
 PV      80
 diesel  57 /
INVs(s) Investment cost of each storage station (€ per kWh)
/ storage 43/
INVi(i) Investment cost of each interconnection option (€ per kW)
/ interconnection 0/
INVsg(s)  Investment cost of each storage generator (€ per kW)
/ storage 0/
INVsp(s)  Investment cost of each storage "pumping" (€ per kW)
/ storage 0/
```

```
MOr(r)   Maintenance and operational variable cost of each resource
(in the case of diesel the fuel cost consumption is included as well
(€ per kWh)
*===diesel generator size aprox. 1000kW fuel consumption at 3/4 Load
198 lt/h, heating diesel fuel price 0.8€/lt -->
/wind      0.0
 PV        0.0
 diesel    0.16/
MOs(s)   Maintenance and operational variable cost of each storage
station (€ per kWh)
/ storage  0.0 /
MOi(i)   Maintenance and operational variable cost of each
interconnection option (€ per kWh)
/ interconnection 0.0 /

FCr(r)   Fixed annual cost of each resource (€ per kW)
*===wind=1-4% of the investment cost  - value selected 1%
*===PV=1% of the investment cost   - value selected 1%
*===diesel=4-8% of the investment cost   -  value selected 4%
*===storage=2-5% of the investment cost  -  value selected 2%
/wind      0.73
 PV        0.80
 diesel    2.28/
FCs(s)   Fixed annual cost of each storage station (€ per kWh)
/ storage  0.86 /
FCi(i)   Fixed annual cost of each interconnection option (€ per
kWh)
/ interconnection  0.0 /
FCsg(s)   Fixed annual cost of electricity generated at the storage
station (€ per kW)
/ storage 0.0 /
FCsp(s)   Fixed annual cost of electricity (pumped) at the storage
station (€ per kW)
/ storage 0.0 /


*===ENVIRONMENTAL PARAMETERS

LCENVFr(r) Life Cycle environmental footprint of the selected
resource (kg CO2 eq per kWh)
/ wind     0.065
  PV       0.150
  diesel   0.770/
LCENVFs(s) Life Cycle environmental footprint of the storage station
(kg CO2 eq per kWh)
/ storage  0.275 /

LCENVFi(i) Life Cycle environmental footprint of the interconnection
option (kg CO2 eq per kWh)
/ interconnection  0.0 /

EMFr(r) Direct emission factor from each energy resource (kg CO2 eq
per kWh)
/ wind   0.0
  PV     0.0
  diesel 0.8 /

LFr(r) Land footprint of each resource plant (km2 per kW)
/ wind   0.0079
  PV     0.0012
  diesel 0.00000064 /
LFs(s) Land footprint of each storage station plant (km2 per kWh)
/ storage 0.00000002 /
```

```
*===SOCIAL PARAMETERS
EMPLr(r) Employment yield of each resource (€ per kWh)
/ wind 0.00099
PV     0.00118
diesel 0.00148    /
EMPLs(s) Employment yield of each storage station (€ per kWh)
/ storage 0.000099  /
EMPLi(i) Employment yield of each interconnection option (€ per kWh)
/ interconnection 0.0  /
SECr(r)  Energy security index for each resource
/ wind  0
  PV    0
diesel -1 /
SECs(s)  Energy security index for each storage station
/ storage 1 /
SECi(i)  Energy security index for each interconnection option
/ interconnection -1 /


SCALARS
Amax  Maximum land being available for the installation in km2
/10000/
PEL   Current commercialisation price of electricity generated (€
per kWh) /0.14/
PEL2  Current commercialisation price of electricity "purchased from
the storage stations"  /0.14/
PEL3  Current commercialisation price of electricity "purchased from
the interconnection option"  /0.14/
PCO2  Current commercialisation price of CO2 (€ to kg) /0.015 /
PEX   Exchange losses from imported energy (and resources) (€ per
kWh) /0.078/
LCREF  Reference Life Cycle environmental footprint of selected ESC
(kg CO2 eq per kWh)/0.065/
np     Storage "pumping" stations charging coefficient /0.9/
ng     Storage generators discharging coefficient /0.9/
nlmax  Maximum storage level coefficient   /1/
nlmin  Minimum storage level coefficient   /0/
nch    Pumpimg - generation coefficient /0.25/
GHGmax Maximum -quality coefficient - for emission permits /0.8/
INTmax Maximum capacity of interconnection option   /0/
INTmin Minimum capacity of interconnection option   /0/      ;


VARIABLES
EGr(t,r)   Energy generation from thermal resources r at time-step t
(kWh)
ESg(t,s)   Energy being generated by storage station at time-step t
(kWh)
ESs(t,s)   Energy being stored at storage station generated from
resources r at time-step t (kWh)
EIN(t,i)   Energy being imported or exported from the
interconnection option i at time-step t (kWh)
ESl(t,s)   Energy storage level
Pr(r)      Nominal capacity of electricity generation plants r (kW)
Ps(s)      Nominal capacity of storage stations  s(kWh)
Pi(i)      Nominal capacity of interconnection option i(kW)
Psg(s)     Nominal capacity of storage generation sg(kW)
Psp(s)     Nominal capacity of storage pumping   sp  (kW)
Z          Total benefit from ESC configuration (€)
ECONV      Economical value
ENVV       Environmental value
SOCV       Social value ;
```

```
POSITIVE VARIABLES  EGr(t,r),ESg(t,s),ESs(t,s),
EIN(t,i),ESl(t,s),Pr(r),Ps(s),Pi(i),Psg(s),Psp(s) ;

EQUATIONS
VALUEECO            Economical value
VALUEENV            Environmental value
VALUESOC            Social value
BENEFIT             Define objective function

CONSmaxr(t,r)       Constraint  maximum capacity for resource r
CONSmaxs(t,s)       Constraint  maximum capacity for energy storage
generation
CONSmaxi(t,i)       Constraint  maximum capacity for interconnection
option i
CONSmaxl(t,s)       Constraint  maximum capacity for energy storage
level
CONSminr(t,r)       Constraint  minimum capacity for resource r
CONSmins(t,s)       Constraint  minimum capacity for energy storage
generation
CONSmini(t,i)       Constraint  minimum capacity for interconnection
option i
CONSminl(t,s)       Constraint  minimum capacity for energy storage
pumping

ESSL(t,s,u)         Energy storage level
SPump(s)            Sizing of the pumping system
SGen(s)             Sizing of the generator
SPs(s)              Maximum Size of the storage station

DEM(t,s,i,u)        Constrain of demand u for time-step t
LANDAV(t)           Land availability limitations  for the set of
selected energy supply options
DIREMI(r,t,u)       Direct emissions (in CO2eq) from each energy
supply resource for the selected Horizon H  ;


VALUEECO          ..  ECONV =E= sum((t,r), EGr(t,r)*PEL)+ sum((t,s),
ESg(t,s)*PEL)+ sum((t,i), EIN(t,i)*PEL)- sum((t,s), ESs(t,s)*PEL2)-
sum((t,i), EIN(t,i)*PEL3)-sum(r,INVr(r)*Pr(r)) -
sum(s,INVs(s)*Ps(s))- sum(s,INVsg(s)*Psg(s))  -
sum(s,INVsp(s)*Psp(s))- sum(i,INVi(i)*Pi(i))- sum(r, FCr(r)*Pr(r)) -
sum(i, FCi(i)*Pi(i))- sum(s, FCs(s)*Ps(s)) - sum(s, FCsg(s)*Psg(s))-
sum(s, FCsp(s)*Psp(s))-sum((t,r), EGr(t,r)*MOr(r))     - sum((t,s),
ESs(t,s)*MOs(s)) - sum((t,s), ESg(t,s)*MOs(s))  - sum((t,i),
EIN(t,i)*MOi(i));


VALUEENV          ..  ENVV =E= sum((t,r), (EGr(t,r)*(LCREF-
LCENVFr(r)))*PCO2)+sum((t,s),(ESg(t,s)*(LCREF-
LCENVFs(s)))*PCO2)+sum((t,i),(EIN(t,i)*(LCREF-LCENVFi(i)))*PCO2);

VALUESOC          ..  SOCV =E= sum((t,r),((EMPLr(r)+(SECr(r)*PEX))*
EGr(t,r)))+ sum((t,s),((EMPLs(s)+(SECs(s)*PEX))*ESg(t,s)))+
sum((t,i),((EMPLi(i)+(SECi(i)*PEX))*EIN(t,i)));

BENEFIT                ..  Z =E= a1*ECONV+ a2*ENVV + a3*SOCV;

*===Energy resources capacity constraints

CONSmaxr(t,r)     ..  EGr(t,r) =L= CFmaxr(t,r)*Pr(r);
CONSminr(t,r)     ..  EGr(t,r) =G= CFminr(t,r)*Pr(r);

*===Interconnection option capacity constraints
```

```
CONSmaxi(t,i)     ..  EIN(t,i) =L= INTmax;
CONSmini(t,i)     ..  EIN(t,i) =G= INTmin;

*===Energy storage capacity constraint in generation and pumping

CONSmaxs(t,s)     ..  ESg(t,s) =L= ng* Psg(s);
CONSmins(t,s)     ..  ESs(t,s) =L= np*Psp(s);

*===Energy storage level constraint

CONSmaxl(t,s)     ..  ESl(t,s) =L= nlmax*Ps(s);
CONSminl(t,s)     ..  ESl(t,s) =G= nlmin*Ps(s);


ESSL(t,s,u)        ..  ESl(t,s)=e= ESl(t-1,s)-
(1/ng)*ESg(t,s)+ng*(ESs(t,s)) ;

SPump(s)          .. Psp(s)=e=nch*Ps(s);
SGen(s)           .. Psg(s)=e=nch*Ps(s);
SPs(s)            ..Ps(s)=l=200000;
DEM(t,s,i,u)      ..  sum(r,EGr(t,r)) + ESg(t,s)-ESs(t,s)+
EIN(t,i)=e=  v(t,u);
LANDAV(t)         .. sum(r,Pr(r)*LFr(r))+sum (s,(Ps(s)*LFs(s))) =L=
Amax;
DIREMI(r,t,u)     ..  EGr(t,r)*EMFr(r)=l= GHGmax*v(t,u) ;


MODEL ENERGY /ALL/ ;
OPTION iterlim = 1000000000 ;
SOLVE ENERGY USING LP maximizing Z ;

ESs.l(t,s)$(not ESs.l(t,s)) = eps;
ESg.l(t,s)$(not ESg.l(t,s)) = eps;
ESl.l(t,s)$(not ESl.l(t,s)) = eps;
EGr.l(t,r)$(not EGr.l(t,r)) = eps;

*=== Export to Excel using GDX utilities
*=== First unload to GDX file (occurs during execution phase)
execute_unload "CP_DEC15_Investment_model_all.gdx" EGr.l, ESs.l,
EIN.l,ESl.l,ESg.l, Z.l, Pr.l, Ps.l,Psg.l,Psp.l,Pi.l,
ECONV.l,ENVV.l,SOCV.l ;

*=== Now write to variable levels to Excel file from GDX
execute 'gdxxrw.exe CP_DEC15_Investment_model_all.gdx  var=EGr.L
rng=ResultsInv!A1:D10000 trace=0';
execute 'gdxxrw.exe CP_DEC15_Investment_model_all.gdx  var=ESs.L
rng=Results_energy-storage!a2:b10000 trace=0';
execute 'gdxxrw.exe CP_DEC15_Investment_model_all.gdx  var=ESl.L
rng=Results_energy-storage!c2:d10000 trace=0';
execute 'gdxxrw.exe CP_DEC15_Investment_model_all.gdx  var=ESg.L
rng=Results_energy-storage!e2:f10000 trace=0';
*=== Write marginals to a different sheet with a specific range

execute 'gdxxrw.exe CP_DEC15_Investment_model_all.gdx  var=Z.L
rng=ResultsInv!H2';
execute 'gdxxrw.exe CP_DEC15_Investment_model_all.gdx var=Pr.L
rng=ResultsInv!i1:k2';
execute 'gdxxrw.exe CP_DEC15_Investment_model_all.gdx  var=Ps.L
rng=ResultsInv!m2:m3';
execute 'gdxxrw.exe CP_DEC15_Investment_model_all.gdx  var=Psg.L
rng=ResultsInv!n2:n3';
execute 'gdxxrw.exe CP_DEC15_Investment_model_all.gdx  var=Psp.L
rng=ResultsInv!o2:o3';
```

```
execute 'gdxxrw.exe CP_DEC15_Investment_model_all.gdx  var=ECONV.L
rng=ResultsInv!H4';
execute 'gdxxrw.exe CP_DEC15_Investment_model_all.gdx   var=ENVV.L
rng=ResultsInv!H5';
execute 'gdxxrw.exe CP_DEC15_Investment_model_all.gdx   var=SOCV.L
rng=ResultsInv!H6';
```